Modelling and Simulation of Building Evacuation in Emergency Conditions - An Agent Based Approach

Dissertation

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To my family and Dominik

Abstract

Evacuation (from Latin *"evacuare"*) is the expression which refers to the movement of people getting away from the source of hazard. In general, evacuations are complex in their dynamics due to the variation of the behavioural responses of individuals as part of evacuating crowds. Independent of the type of emergency, evacuation times are a common design measure for guaranteeing personal integrity for people inside of buildings. The accomplishment of design standards regarding evacuation times leads in practise to modifications of architectural design and construction materials of new buildings. Modifications in historic buildings are in contrary limited due to their cultural significance and difficulty of adaptation to modern safety standards. In addition to this, general safety regulations do not cover all aspects required for preventing fatal incidents due to evacuations. In this sense, the study of evacuation dynamics is relevant to the reduction of risk of fatal events.

The present thesis proposes a mathematical model for the description of the behavioural dynamics of controlled evacuations based on visual perception. The object-oriented model of *PerPedES* (Perceiving Pedestrian Evacuation Simulator), which was developed for this thesis, describes the global dynamics of an evacuation by means of individual rules. Walking direction and speed of the modelled pedestrians are obtained based on information derived from a model for visual perception utilising a modified ray-tracing. Within *PerPedES*, an individual criterion for moving decision motivated by psychological considerations is introduced. The resulting traces of simulated evacuations present similar characteristics to motion patterns described in literature. In particular, arch- and lane-formations, clogging-effect, overtaking- and collision-avoidance manoeuvres.

Within the context of risk reduction in the built environment, the presented behavioural model is applied in a case-study. In particular, for the analysis of the vulnerability of the occupants of the *Uffizi Gallery* in Florence, when pursuing an evacuation. In this thesis, mean evacuation times and individual walking speeds were computed together with the evacuation traces left by the occupant.

Zusammenfassung

Evakuierung (vom lateinischen Wort *"evacuare"*) beschreibt die Bewegung von Menschen weg von einer Gefährdung. Generell sind Evakuierungen komplex in ihrer Dynamik. Dies liegt begründet in der Individualität von menschlichen Reaktionen innerhalb von Menschenmengen. Für die Gewährleistung der Sicherheit von Personen innerhalb von Gebäuden ist die Evakuierungszeit, unabhängig von der Art einer Notsituation, von entscheidender Bedeutung. Die Umsetzung baulicher Standards mit Bezug auf Evakuierungszeiten führt in der Praxis zu Modifikationen an Architektur und Material neuer Gebäude. Modifikationen an historischen Gebäuden können hingegen aufgrund von Denkmalschutzbestimmungen modernen Sicherheitsstandards nicht genüge tragen. Zusätzlich dazu decken allgemeine Sicherheitsregulierungen nicht alle Aspekte ab, die erforderlich sind, um fatale Vorfälle auf Grund von Evakuierungen zu vermeiden. In diesem Sinne ist die Untersuchung der Dynamik von Evakuierungen für die Reduktion solcher fatalen Ereignisse von großer Bedeutung.

Die vorliegende Arbeit präsentiert ein mathematisches Modell für die Beschreibung des dynamischen Verlaufs von kontrollierten Evakuierungen, welches auf visueller Wahrnehmung basiert. Das Modell des für diese Arbeit entwickelten Objekt-orientierten Simulators *PerPedES* (Perceiving Pedestrian Evacuation Simulator) beschreibt die globale Dynamik einer Evakuierung auf Basis von individuellen Zuständen einzelner Modellfußfänger. Die Laufrichtung und Geschwindigkeit dieser Modellfußfänger wird auf Basis eines Modells für visuelle Wahrnehmung ermittelt, welches ein modifiziertes *ray-tracing* verwendet. Innerhalb von *PerPedES* wird ein individuelles Kriterium für Bewegungsentscheidungen eingesetzt, welches von psychologischen Betrachtungen motiviert ist. Die aus Simulationen resultierenden Laufwege weisen ähnliche Charakteristika auf, wie in der Literatur dokumentiert. Nachvollzogen werden konnten insbesondere Bogen- und Schlangenformierungen, Verstopfungseffekte und Überholmanöver sowie Kollisionsvermeidung.

Im Kontext der Risikoreduktion in Gebäudeumgebungen wurde eine Fallstudie durchgeführt, welche die Vulnerabilität von Besuchern der *Uffizi Gallery* in Florenz untersucht. Dabei wurden sowohl mittlere Evakuierungszeiten, als auch statistische Verteilung der Laufgeschwindigkeiten während einer Evakuierung und Wegspuren berechnet.

Resumen

Evacuación (del latín *"evacuare"*) es la expresión que comúnmente se refiere al movimiento de personas alejándose de la fuente de peligro. En general, la dinámica de evacuación es compleja debido a la variación en el comportamiento de los individuos durante la misma. Independientemente del tipo de emergencia, el cálculo del tiempo de evacuación es una medida común de diseño, la cual busca el aseguramiento de la integridad física de las personas que se encuentran en el interior de un edificio. El cumplimiento de los estándares de diseño correspondientes al tiempo de evacuación en edificios nuevos, puede resultar (en la práctica) en la modificación del diseño arquitectónico y/o de los materiales de construcción del mismo. Por el contrario, en el caso de edificios históricos dichas modificaciones están limitadas debido en parte al significado cultural o bien a la dificultad de adaptación del edificio a los estándares modernos de seguridad. Además, las regulaciones en materia de seguridad por lo general no cubren todos los aspectos necesarios para la prevención de incidentes fatales derivados de una evacuación. En este sentido, el estudio de la dinámica de evacuación resulta de gran importancia para la reducción del riesgo de ocurrencia de incidentes fatales.

La presente tesis propone un modelo matemático para la descripción de la dinámica conductual en el caso de evacuaciones controladas, tomando como base la percepción visual del individuo. El simulador *PerPedES* (por su siglas en inglés *Perceiving Pedestrian Evacuation Simulator*), un modelo orientado a objetos y desarrollado para ésta tesis, describe la dinámica global de una evacuación por medio de reglas individuales. Tanto la dirección como la velocidad al caminar del peatón representado son calculadas tomando como base la información derivada del modelo de percepción visual, el cual utiliza un algoritmo modificado de *ray-tracing*. Dentro de *PerPedES*, se introduce un criterio individual para la toma de decisiones en cuanto al movimiento del peatón, cuyo enfoque está basado en la psicología de la percepción. Las trayectorias de evacuación resultantes de las simulaciones realizadas presentan características similares a los patrones de movimiento descritos en la literatura; en particular, en cuanto a la formación de arcos y líneas, a los efectos de obstrucción, rebasamiento y las maniobras de evasión correspondientes en el caso de una posible colisión.

En el contexto de la reducción de riesgo en edificios, el presente modelo conductual es aplicado a un caso de estudio. Específicamente, para el análisis de la vulnerabilidad de los ocupantes del edificio en cuestión (en este caso de la *Galería Uffizi* ó *Galleria degli Uffizi* en Florencia, Italia) cuando la evacuación del mismo es llevada a cabo. En la presente tesis, se calcularon los valores medios del tiempo de evacuación y de velocidad individual junto con las trayectorias de evacuación trazadas.

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Alicia G. Jürgens-Ortega
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Chapter 1

Introduction

One main contributing factor for human safety in the built environment is the possibility of effective and efficient evacuation. Construction norms and building-codes suggest, independent of the type of emergency, the comparison of available and required evacuation times as a measure to guarantee personal integrity of people inside a building [195]. Evacuations are highly complex in their dynamics, since behavioural responses vary from one individual to another and according to the situation experienced. However, none of these factors can be clearly specified and evaluated by the current methods for calculating evacuation times [197]. Together with this, the adaptation of a building to safety standards in order to increase its level of safety (in the practical sense) may lead to modifications of its construction materials and architectural design. In case of historic buildings, modifications are limited due to the cultural significance of the building, technical limitations or high costs that may imply. In cases like this, other solutions have to be found: for instance to restrict the number of visitors or to avoid a high concentration of persons in certain locations of the building. These types of strategies require simulations. In this sense, the simulation of evacuation processes is a state-of-the-art tool in safety engineering of built environments, since it facilitates the evaluation of possible evacuation strategies. This chapter presents a general introduction to the field of evacuation dynamics and discusses the main concepts of safety inside buildings. Moreover, Section 1.2 presents the definition of the problem to be developed through this study and the motivation for it. The scope and objective of this research is given in Section 1.3. Finally, the methodology and organisation of this work are presented in Section 1.4.

1.1 General Remarks

The construction of new buildings implies many requirements of design, engineering and safety. Construction norms and standards worldwide establish the *physical integrity* of the occupants of a building as one of the major requirements to be met (from the early design until the building is opened to the public[1]). Safety regulations in the built environment recommends the implementation of active or passive infrastructure as preventive and first-response actions in case of an emergency. Examples of this are the introduction and use of proper emergency signal codes, fire extinction systems, and evacuation routes[2]. During the past decade, performance-based regulations due to fire-safety in building-design were introduced by many countries like the United Kingdom, New Zealand, Norway and Japan. Some years later, this trend was followed by other countries like the U.S.A, Canada, Korea and the European Union. The scope of performance-based regulations proposes the introduction of proper and specific fire-safety objectives as regulatory means [104, 130, 172]. In other words, this new approach contributes to the introduction of new building-design methods by defining qualitative and quantitative measurements of safety in the built environment [15, 49, 263]. These activities imply, in addition, periodic evaluations and improvements as part of an integral safety management of the building.

Nevertheless, the existence of fatal incidents (e.g. King's Cross Fire, U.K. 1987, overcrowded Düsseldorf Stadium, Germany 1997, WTC terrorist attack, U.S.A. 2001, Pilgrims stampede, Mecca 1990 and 2006), exhibits a more complex context in the built environment commonly beyond to the general cases covered by construction norms and safety regulations alone.

1.2 Problem Definition and Motivation to this Study

Evacuation time is a relative common and widely extended parameter regarding safety inside buildings [54, 196, 230]. Nowadays there are two methods for the calculation of the required time for evacuating a building [240]. The first one is the so-called hydraulic model, which is based on "hand-calculations". This method calculates the required evacuation time by considering the capacity of the building, averaged walking speeds and distances from several locations of the building to predefined exits [223, 228, 230]. The second method considers

[1]Eurocodes, OSHA Standards, NBC-Standards

[2]EN 1990: Eurocode 0 (European territory), OSHA-Parts 1910 and 1926 (U.S.A.), NBC-1995 and 2005 (Canada), ABCB 1996 (Australia)

the evacuation process to be the sum of the activities achieved before, during and after the evacuation [15, 171]. The advantage by using these methods remains in their easiness of calculation. However, their results should be regarded with caution, since the activities that take place in evacuating scenarios are very ambiguous [240]. Moreover, the variety of architectural design and the use of the building (i.e., theatre, stadium, school, hospital, etc.) adds more complexity to the evacuation.

The study of evacuation dynamics has been the point of interest to the scientific community for the last decades. Part of this interest is directed to the complexity that such a process represents and to its application to other fields. Several studies regarding evacuations identified the development of diverse kinds of interactions between the people inside a building, in particular of the type: individual-individual, individual-building, individual-group of persons [102, 197, 221]. Those interactions may split into several sub-processes or activities (e.g. emergency recognition, warning, preparation to movement) prior to the evacuation itself. However, the available information regarding this is insufficient for a clear estimation of the nature and duration of the upcoming processes prior to an evacuation.

A central point on the study of evacuation dynamics is (in a first instance) the understanding of human behaviour individually [223]. The second is related to the study of crowds. A *crowd* is commonly seen as a group of interacting individuals with apparently no common goal [153, 161, 223]. When an emergency occurs the kind of interactions change, and in some cases the resulting behaviour may escalate into violence or panic [224, 226]. In the evacuation of buildings, crowds are always involved. And therefore a major understanding on the development of these interactions is crucial. Until now, many models for simulating crowd dynamics during evacuation of buildings have been developed with basis on engineering, biology or psychology approaches (Chapter 3, Figure 3.1). However, there are many questions regarding the simulated behaviour of the crowd, and their validation within real situations is still unclear [209, 223]. Moreover, the engineering and psychology approaches are characteristically mutually exclusive in their focus. For instance, in the engineering approach individuals are assumed to be dynamic objects whose behaviour keep similitude to those subjected to physical laws. This has lead to the simulation of fluid or particle dynamics and potential fields [110, 119, 124, 214]. In opposition to this, models based on the psychology consider crowd members as individuals who think and act according to the situation [223]. In other words, the dynamics described by a crowd are the result of the perceived surrounding of its members and not as a result from modified physical laws [134, 256]. The biology approach, in contrast, describes the interactions in the crowd as a particular type of self-organisation (as seen in several biological systems). A first and widely referred model in this field is the one suggested by Reynolds [200]. Although the study of self-formation in biological systems is not new, it provides a novel alternative for describing pedestrian dynamics. In this sense, models for describing path-motion (for instance, way-finding applied to robotics) [19, 20, 68, 211, 234] provided new understanding in crowd dynamics. However, the application of this type of models to the study of crowd dynamics is still under development [95, 96, 97, 150].

According to Sime [221], *vulnerability* of the occupants of a building is defined as the susceptibility of the occupants to be involved in an accident and/or being injured. This susceptibility depends on three main factors: the characteristics of the individuals, the actions that the individuals take inside the building and the characteristics of the building itself. A precise knowledge about how this vulnerability may change according to the situation (normal or emergency) cannot be clearly obtained by means of the available models of crowd dynamics. Even though actual regulations of safety inside buildings considers the calculation of evacuation times as a measure to increment the level of safety of the persons inside a building, the actual methods for calculating evacuation times do not consider the vulnerability of the occupants at the moment of an evacuation. In the present study it is believed that due to the nature of the evacuation phenomena, the sole use of construction and design norms for buildings as a measure of safety represents a limited solution to the problem of evacuation dynamics. In this sense, further efforts should be focused on the development and improvement of mathematical models able to describe collective behaviour during evacuation processes with basis on the psychology of cognition. Moreover, the use of such models shall enable the measurement of vulnerability of the occupants of a building within an evacuation.

1.3 Scope and Objective of the Research

The present study is focused on the development of a mathematical model for the simulation of evacuation dynamics in normal situations based on visual perception. Flexibility in the model is expected in a way that further extensions and improvements shall be possible. Moreover, within the context of safety in the built environment, the use of the model shall facilitate the analysis and quantification of vulnerability of the occupants of a building when pursuing the evacuation of a real-case building. In particular, a historic building (the Uffizi Gallery). For this purpose, the study of evacuation dynamics within the context of Risk Management in the built environment is introduced here.

1.4 Methodology and Overview of this Work

For the achievement of these objectives, the present thesis has been structured in the following way.

- Regarding to Risk Management in the built environment, **Chapter 2** introduces the importance of the study of evacuation dynamics and discusses the implementation of further methods for the reduction of risk of fatal events derived from evacuation processes. In this sense, Section 2.1 discusses design criteria and their potential influence regarding safety inside of buildings. Section 2.2 suggests the use of a simplified Risk Management Methodology as an alternative solution to the reduction of fatalities due to evacuation processes. Therefore, vulnerability inducing factors are of especial interest in this work.

- **Chapter 3** gives an overview of the state-of-the-art regarding modelling of collective behaviour in evacuations. Section 3.1 is focused on the fundamentals of evacuation dynamics and their characteristic self-formations. Although the field of evacuation dynamics is a relatively new area of interest, several strategies have been developed for their modelling. Until now, there are no clear issues for classifying the existing models for pedestrian dynamics. However in the present work, a general classification is suggested in Section 3.2. Moreover, this section reviews the criteria and main assumptions considered in each (presently) existing model for describing evacuation dynamics. In general terms, the study of a crowd and their dynamics varies on the way in which this and its elements are defined. In this sense, pedestrian dynamics inside a crowd can be explained macro-, meso-, or microscopically. The capabilities and limitations to these approaches are discussed in Section 3.3. In this study, pedestrian dynamics are understood as a self-formation phenomenon, where emergent formations are the result of interactions among the members of the crowd and their surrounding environment. This leads to the fulfilment of several requirements regarding the modelling of evacuation dynamics given in Section 3.4.

- The present study is focused on the development of a new model for describing evacuation dynamics with basis on psychological cognition. Therefore, **Chapter 4** focuses on this field and provides an overview of the most relevant aspects of individual (Section 4.1) and collective behaviour (Section 4.2). Any behavioural response of an individual is influenced by subjective and objective factors inherent to the human nature. For simplicity, our proposed model only considers the objective part of a behavioural response and the corresponding response-elaboration processes. Being visual perception of special interest for this study. Therefore, only the sensorial data which have been visually "perceived" by the individual will influence its behavioural response, and the corresponding interactions to the environmental surrounding as suggested in the Ecological Theory of Gibson [87, 88].

- **Chapter 5** presents the behavioural model (PerPedES) and its mathematical formulation (Section 5.1). As an introduction to this approach, Section 5.1.1 presents the modelling implications of evacuation dynamics in normal situations. Within this model, the dynamics of the system *crowd* are described by means of individual states. These states define the position $\boldsymbol{x}$ and walking direction θ of each individual within the evacuation as shown in Section 5.1.2. Moreover, explicit Euler-scheme with Randomised Gauss-Seidel-like updates (an integration scheme) has been implemented for the approximation of the dynamics (Section 5.1.5). A central part of behavioural modelling is the introduction of individual visual perception skills, which permits the adaptation of the behavioural response to the current situation. In this sense, a simplified OO-model for visual perception in evacuation dynamics is developed and presented in Section 5.1.6. Due to the lack of information and standardised criteria regarding behavioural responses of the individuals and their interactions in real evacuations, an alternative validation of the model based on the qualitative description of emergent motion-patterns proper to evacuation dynamics is introduced in Section 5.2. In accordance to the numerical results, consistency to small time-steps was found. Meanwhile, convergence of the results is assured by time-step sizes below 0.2 seconds and for an amount of eight sampling rays or higher (Section 5.2.2). Computation time required for the simulations is shown in Section 5.2.3. Finally, the capabilities and limitations of the behavioural model are discussed in Section 5.3.

- Within the context of risk reduction in the built environment, the behavioural model was introduced as a tool for the analysis of those factors which may affect the vulnerability of the occupants, when pursuing an evacuation of the Uffizi Gallery. In this sense, **Chapter 6** present the mean evacuation times and individual walking speed registered for six scenarios together with the evacuation traces left by the agents. Demographic characteristics of the visitors and the Uffizi Gallery, relevant to the study of vulnerability, are shown in Sections 6.1 and 6.2. Meanwhile, simulation results are given in Section 6.3. Concluding remarks to the numerical results are given in Section 6.4.

- The main body of the thesis ends in **Chapter 7** with a summary of key results and contributions to research of this thesis, together with the recommendation to future works.

Chapter 2

The Study of Evacuation Dynamics and Risk Reduction

This chapter presents the available instruments for safety in the built environment. The introduction of these instruments is based on the application of several construction standards and norms. Historical examples of fatal incidents within evacuation dynamics suggest that safety in the built environment should not be restricted to the exclusive fulfilment of design and construction criteria. In this sense, Section 2.1 stresses the need of the introduction of further potential factors to the actual engineering-based solution to safety inside buildings. An example of those (until now) not considered factors is the behavioural response of the occupants of the building under study. Nevertheless, the isolated use of preventive and reactive instruments for safety do not always guarantee the maintenance of the intended level of safety. In this sense, the additional application of active instruments (in particular, the use of management methodologies), represents an alternative solution to safety regarding evacuation processes. In Section 2.2 the application of a Risk Management Methodology for evacuation dynamics is suggested. In addition to this, risk of fatal events regarding evacuations is defined. In the same way, the most frequent factors associated to fatal events due to evacuations are determined: the source of hazard, the vulnerability and exposure of the occupants of the building. The present study is focused on the study of the vulnerability of the occupants of the building and its influence over the evacuation times. In which, a central point in this research is the introduction of simulations of evacuation dynamics as a source of evacuation data.

2.1 Evacuation of a Building and its Influencing Factors

A generalised practise within safety in the built environment is the use of design and construction norms and standards. However its exclusive application should be taken with caution. This is mainly because of their restrictive focus on procedural applications and eventual provisions in case of an emergency. These advises are given in a general way and most of them are related to the regulation of shapes and dimensions to be fulfilled by the design of the building. Thus, their application is given in a generalised form. This implies that specific cases are not possible to be regulated, leaving then this task to the professional criterion (and experience) of engineers and designers. An example of this, is the principle taken regarding crowd dynamics and level of safety. In this sense, safety inside buildings is assumed to be in close relation to calculated evacuation times.

In order to give an introductory view to this problem, this section shows a brief summary of historical examples of fatal incidents related to evacuation dynamics inside buildings. Moreover, the diversity of the example events shown in Table 2.1 reinforces that crowd safety depends on many other factors, until now not considered by the engineers [18, 222]. In addition to this, a summary of the potential influencing factors within safety in the built environment is provided.

2.1.1 Historical Examples

The study of evacuation dynamics began as a manner to decrease the frequency of deaths or injuries caused by evacuations of buildings [79, 80, 139]. Table 2.1 summarises some examples of fatal incidents regarding evacuations.

The causes and the scenarios in which fatalities take place are varied (Table 2.1). However, two points are remarkable. First, the starting event of the disaster is not always related to external events (e.g. fire, weather, natural disasters), but other factors may contribute (like overcrowding, unexpected events or behaviour). Second, most of the events with high number of deaths or injures are related to the behaviour of the crowd or to the management of the emergency, but it may not be limited to them. For purposes of this study, the most frequent potential factors associated to fatal events are here summarised and classified into three categories (Table 2.2).

From Table 2.2 is observed that fatal incidents due to emergencies inside buildings may be associated to technical (failures in the infrastructure) or behavioural reasons (occupants response). In the first case, a failure on the design

Date	Place	Venue	Death	Injured	Reason
1863	Santiago, Chile	Church	2000	-	Unknown
1881	Vienna, Austria	Theatre	570	-	Emergency egress
1902	Ibrox, UK	Stadium	26	517	Collapse of West Stand
1943	London, UK	Tube station	173	92	Ingress
1971	Salvador, Brazil	Stadium	4	1500	Fight and wild rush
1982	Moscow, USSR	Stadium	340	-	Re-entering fans
1990	Mecca, Saudi Arabia	Pedestrian tunnel	1425	-	Overcrowding
1997	Düsseldorf, Germany	Stadium	1	> 300	Overcrowding at concert
1998	Chervonohrad, Ukraine	Cinema	4	-	Stampede
2000	Lisbon, Portugal	Nightclub	7	65	Poisonous gas bombs
2001	New York, USA	WTC	2603	6291	Terrorism
2010	Duisburg, Germany	Pedestrian tunnel	21	500	Overcrowding

Table 2.1: Summary of historical crowd disasters in evacuation processes and collective events. Extracted from [63, 81, 210] and updated.

or characteristics of a infrastructure of the buildings may contribute to escalate the emergency [99]. However, they do not always initiate the emergency situation [204]. In the second case, the behavioural response of the occupants of the building at the moment of emergency (i.e. adaptation to new or unfamiliar situations) may induce or even escalate the emergency [11].

2.1.2 Design Parameters Regarding Safety Inside Buildings

The design of a new building or the renewal of an existing one requires the achievement of several parameters of safety. Regarding to safety three main instruments are commonly applied in the built environment. These instruments are here classified into *preventive, active* and *reactive*. In one hand, *preventive* instruments are focused on the avoidance of possible instances which enables the escalation or appearance of an emergency. Most of these instruments are related to building and construction *norms* and *standards*. However, its exclusive use do not always guarantees the desired safety level of the occupants. Thus, its application should be done with caution. Moreover, inconcordance about the applicability of several standards and measurements increases the problematic [233]. In the other hand, *active* instruments of safety are focused on systematic tools or *methodologies* that sustain the desired level of safety in the building at

Infrastructure	Use other than designed [18] Overload of the building [11, 233] Failure of the system [18] Deficient emergency management system [261]
Initial Events	Natural disasters (extreme weather, earthquakes, avalanches) Man-made disasters (fire, structural failures) [99, 129] False alarms Phantom panics [153] Terrorism [82]
Occupants	Characteristics of the participants (age, disabilities, size) [221] Behavioural responses (stress, fear, anger) [18] Internal communication [81, 224]

Table 2.2: Frequent sources of risk and potential inductive factors for fatal events in the built environment.

any time. The most common ones are referred to methodologies regarding fire mitigation and crowd management. Meanwhile, *reactive* instruments are those focused on the *control* of an existing emergency situation but not to its prevention. The application of these instruments regards to the use of equipment (like in the case of fire mitigation) and control manoeuvres of people as the suggested by crowd control. In the present section the most relevant instruments are reviewed.

Construction and Design Regulations

As its definition says, preventive instruments are focused on the prevention of scaled emergency situations. Most of these are related to the application of design and construction norms and standards. To provide a complete list of the available normativity applicable to safety in the built environment is out of the scope of this study. However, common international construction, design codes and standards are shortly summarised as follows.

- European Codes on Structural Design (Eurocodes),
- British Standards on Accesibility, Fire and Building Safety,
- Standards from the Occupational Safety and Health Administration (OSHA),

- Canadian and Australian Codes on Fire and Building Safety,
- Green Building Guide,
- Technical Guides of the National Fire Protection Association (NFPA),
- National Institute of Standards and Technology (NIST) Guidelines,
- Technical Guides and Reports of the Federal Emergency Management Agency (FEMA), and the
- Society of Fire Protection Engineers (SFPE).

According to professionals in this field, a safe design of a building considers issues related to its location, shape, dimensions (e.g. emergency routes, doors, travel distances, capacity) but also construction materials and their dimensions [11, 81, 129, 160, 204]. Most of these considerations are suggested in the regulations mentioned before. Then a central point in crowd safety is the calculation of evacuation times [186, 195, 222]. Evacuation time values are frequently associated to design criteria of buildings, since its calculation is based on the architectural shape and dimensions of the building under consideration and because of its easiness of calculation.

Calculation of Evacuation Times

The use of a calculated evacuation time for a building is a relative common and widely extended measure regarding safety. Actual safety dispositions consider standardised models for calculating evacuation times [54, 196, 230]. In general, there are two methods of calculation: *the hydraulic model* and those based on evacuation models [240]. The first method considers architectural-design characteristics of the building (i.e, maximal capacity of occupancy, distances to the exit or exits given by a predefined evacuation route) together with assumed averaged walking speeds [223, 228, 230]. This model is commonly considered to be a “hand-calculation” type because its easiness of use. However, its application is suggested for cases of low concentrations of people, or when the reliability of the results do not represent a critical point regarding safety issues [240]. Meanwhile, the second approach defines several behavioural sub-processes together with an hypothetical (but possible) fire-development occurring along the evacuation process (like ignition-, alarm-, premovement- and movement-times) [15, 171]. Additionally, this model also considers the existence of several interactions (in particular of type: individual-individual,

individual-building and individual-group of persons) [102, 197, 221], where several sub processes which may appear previous to the evacuation itself (e.g. emergency recognition, warning, preparation to movement) are the result of those interactions.

In general terms, *evacuation dynamics* studies the dependencies between those interactions and their upcoming processes before, during and after an emergency situation, and when an evacuation takes place. In this sense evacuating a building represents a complex issue, where the time needed by the individuals to move to the nearest exit is not an unique process to calculate [171, 222, 223]. In fire prevention and safety inside buildings, the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) are the behaviour-based measures most commonly referred [192, 195]. The ASET relates the available evacuation time due to the ignition properties and materials present in the building which may produce or extend a fire during an emergency [53]. The RSET relates the behavioural procedures of evacuation followed by the individuals inside a building. In general, the RSET consists in two main points: the time taken to achieve activities "previous" to the evacuation, the so-called *premovement time* (i.e., alarming, emergency recognition and preparation to evacuate) and the time of the evacuation itself or *movement-time* [40, 220]. Although the RSET considers many aspects of behavioural procedures due to an evacuation, still many other aspects like psychological response of the occupants (especially those related to the premovement times [185, 197]), architectural design of the building and emergency management manoeuvres may also influence the evacuation process [171, 186, 219]. Besides the complexity in building design, the understanding of human behaviour is a central point for obtaining reliable evacuation models [143, 222, 223] and for the reduction of fatal events. This represents a challenging field of research.

2.1.3 Implications to this Study

In Section 2.1 potential factors which may influence the intended level of safety inside buildings were presented and classified. The analysis of fatal events of crowds shows that safety in built environment is not limited to the exclusive fulfilment of design and construction requirements. In this sense, the response of the occupants to an emergency and their relation to the infrastructural conditions of the building shall play a central role for the design. Nevertheless, the use of isolated preventive and reactive instruments of crowd safety do not guarantee the maintenance of the level of safety. In this sense, active instruments and in specific the use of management methodologies represent an alternative and integral solution in the field of evacuation dynamics.

2.2 Active Safety: A Risk Management Methodology

Almost two decades have past since professionals in crowd safety suggested for the first time the implementation of additional instruments as a manner to prevent fatal events [80, 81]. In which, further factors like the behavioural response of occupants inside a building should be introduced to the existing engineering-based tools for crowd safety [171, 197, 219, 222, 223]. Parallel to this, Sime [222, 223] addresses an alternative solution to the safety inside buildings. This approach introduces a relationship based on four factors: design and engineering requirements, communication technology, crowd management methodologies and the study of crowd behaviour and dynamics [222]. In addition, the use of crowd management methodologies is discussed and referred as an alternative and more comprehensive solution to safety in the built environment [11, 17, 47, 261, 264]. Until now, several methodologies for crowd management have been developed [47, 79, 80, 99, 170, 240]. These methodologies suggest a more structured and comprehensive approach, however they do not consider the reduction of potential risks. In the present study, the methodology for risk management suggested in [190] is suggested as an alternative solution of to the evacuation dynamics problem. For this purpose, a definition of risk of fatal events in the built environment (Equation 2.2) is here suggested (Section 2.2.2) together with the corresponding implications to evacuation dynamics.

2.2.1 Fundamentals of Risk Management

In emergency occurrence (natural or man-made) it is frequent to refer the need for management systems as a tool for risk reductions [49, 170]. However, risk should be first defined in order to become able to be reduced. According to Proske [194], the definition of risk strongly depends on the context where the object of study is located (e.g. financial-risk, environmental-risk, technical-risk, health-risk, social-risk). Therefore, a single definition of risk cannot always be applied. Within the work of Pliefke et al. [190] several definitions of risk regarding disasters were reviewed. In addition, the definition of *risk*, independent to the context of the object of study, should involve the terms of *hazard, loss, damage, vulnerability, exposure* and *consequences*. However, still a structured methodology for risk reduction is needed. In this sense, the PEER Equation (an earthquake engineering equation commonly used for risk reductions) [191] (Equation 2.1) is frequently referred, since it suggests a generalised methodology for decision-making regarding risk estimations and their probability of occurrence. In general terms, the PEER Equation considers the evaluation of a determined decision regarding a specific risk by considering three main factors: (i) the specific hazard intensity, (ii) the response of the studied system (building location and design) to that hazard intensity and (iii) the potential damages and losses that the decision under consideration may overcome. Although the PEER Equation encloses a methodology, a non-rigorous mathematical expression is given:

$$g(\text{decision}) = \iiint p(\text{loss}) \cdot p(\text{damage}) \cdot p(\text{response}) \cdot p(\text{frequency}) \tag{2.1}$$

The PEER Equation is helpful especially when the probability functions of loss, damage and response to a given hazard intensity are known. In most of the cases, even estimations are not known or its calculation cannot be achieved due to the lack of available information. However, the application (by means of a defined methodology for risk reduction) of the PEER Equation could be extended to other contexts where risk is to be determined (e.g. financial, environmental, technical, social). In this sense, the broad nature of risk allows the application of risk reduction methodologies in fields like evacuation dynamics. Then, the proposed methodology (Risk Management Chain Methodology, RMCM) published in [190, 252] is here introduced as an alternative solution regarding the reduction of risk of fatal events due to evacuation processes.

In general terms, the RMCM (Figure 2.1) consists of three main steps: *risk identification, risk assessment* and *risk treatment*. The fist step (risk identification) corresponds to the identification of all possible risks that may be present in the studied system, where the adequate system and definition of boundaries is important. Once all the possible risks have been identified, each risk is analysed and judged. These corresponds to the so-called risk assessment. Meanwhile, risk analysis can be seen as the *"operative step"*. Here the vulnerability of the system under specific hazards intensity can be quantified and potential damages or losses can be distinguished. Depending on the definition of the system, it can occur that not the whole system is under the same risk or at risk at all, but a part of it. Therefore a classification of elements of the system is convenient. Such classification consists of the distinction among elements of the system that are under a determined risk (*Elements at Risk*, EaR) and those which are not (*Elements at No Risk*, EaNR). Once the analysis of risk on each EaR has been done, an assessment of those risks is the next to perform (the so-called *"evaluation step"*). At this point, all risks are graded (for example, into low, medium, high or in any other scale) and compared between each other. With this information

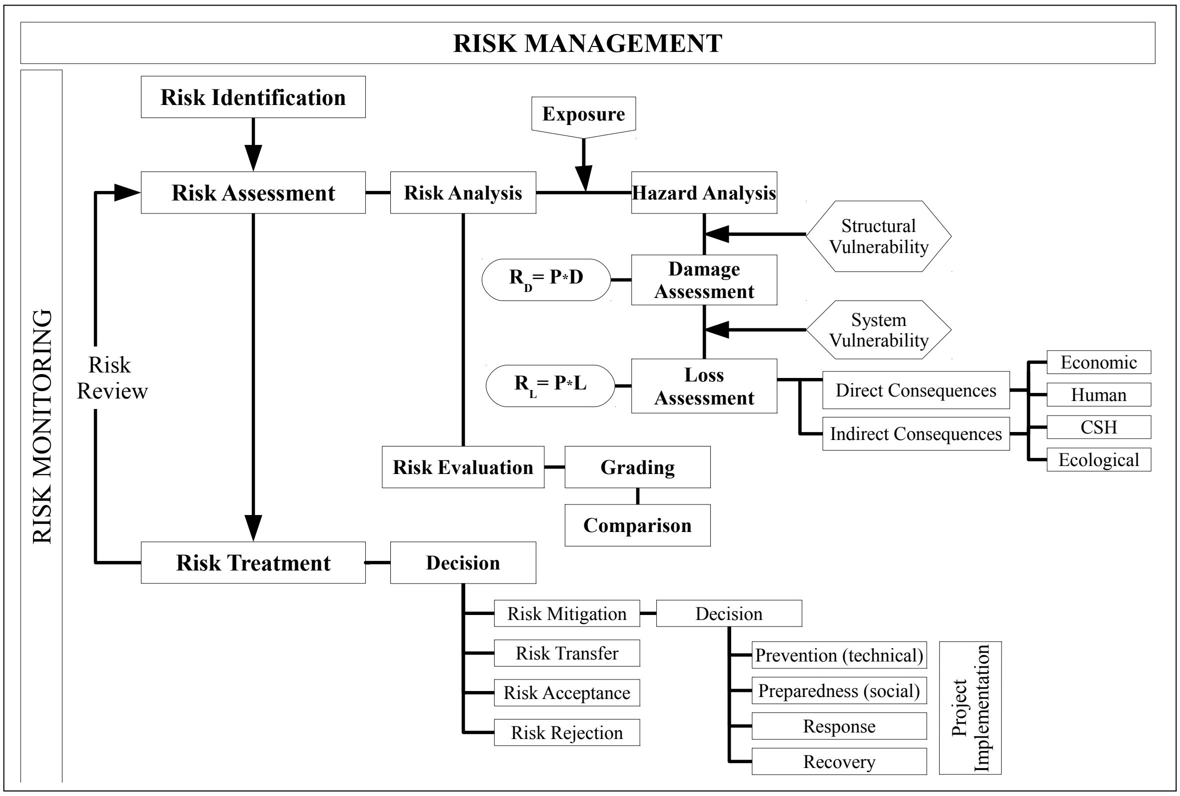

Figure 2.1: Overview of the risk management chain methodology for disaster management, as suggested in [252].

it is possible to distinguish between risks and to prioritise them. According to the relevance of the risk and its influence into the system, they can either be mitigated, transferred, accepted or rejected (the so-called risk treatment). Only when it is decided to mitigate the risk, a preventive (technical or social) response and recovery phase can be implemented. Moreover, a review of the evolution of the risks as a *"monitoring step"* is included. This step provides two advantages: first, the actual-state of the system is known. Second, new hazards to the system can be identified and properly managed.

Application of Models for Evacuation Dynamics in the Reduction of Risk

Safety inside buildings is a challenging task to be achieved. Specialists in the field have suggested several tools in this sense. The most used ones are the performance-based regulations, which suggest the definition of generalised objectives regarding safety and the implementation of strategies for its achievement [15, 49, 104, 130, 172, 263]. However fatalities still occur, and new regulation tools have been introduced. An example of these is the calculation of evacuation time [54, 196, 230]. A realistic calculation suggest the application of evacuation models, where human behaviour-based processes (like premovement activities) are taken into account [15, 171] and related to the architectural design of the building in the context of an evacuation. However, a correct identification of potential risks for occupants at the moment of an evacuation cannot be achieved by this mean. This, because of the existing lack of knowledge about the real behaviour of the individuals at time of evacuation and the potential effect of architectural design of the building on the behaviour itself [221].

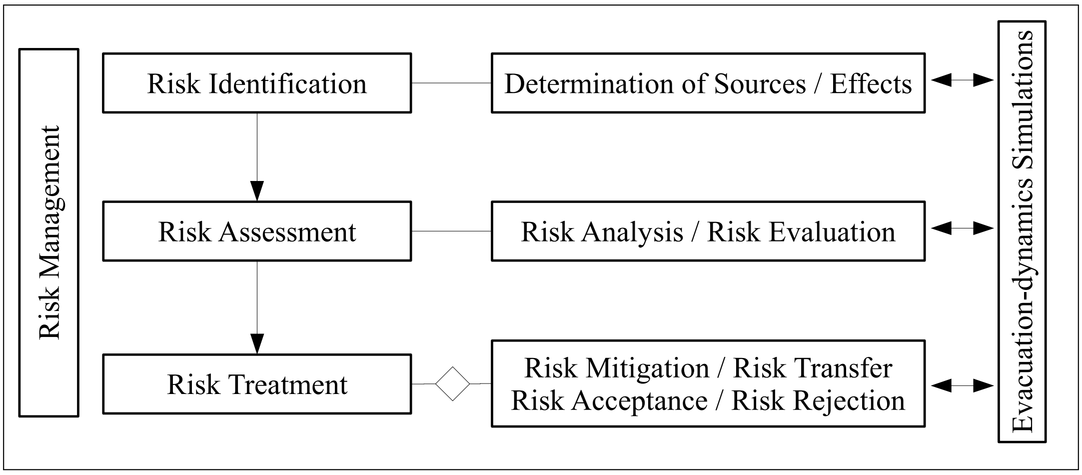

Figure 2.2: A simplified risk management methodology for evacuation dynamics. The incoming information to the framework is the result of runned simulations of evacuation scenarios.

In this sense, the uses of risk management methodologies (like the suggested in [190, 252]) represents an alternative tool regarding safety inside buildings and the reduction of risk of fatal events. The application of this methodology allows the correct identification of potential risk to the occupants due to the architectural design of buildings. Moreover, the elaboration of plans and strategies for the reduction or treatment of risks in accordance to each situation are possible. However, due to the nature of fatal events (difficult to predict and to repeat) a correct identification of risk is a challenging problem. Then, simulations of crowd behaviour in evacuations represent a source of data [80, 115, 145, 149, 173], since by running a simulation the repetition of a determined event is possible and adds certain degree of flexibility in the study (e.g. characterisation of the system and its elements). By this means, those problable sources and effects of a determined risk involved within an evacuation can be identified, analysed, evaluated and treated. This requieres of models describing realistic evacuation dynamics. For this purpose, the integration of such models as a tool in for the management of risk within evacuations is suggested here (as shown in Figure 2.2).

2.2.2 Definition of Risk in Evacuation Dynamics

In the last four decades, the behaviour of masses in several contexts have been studied. From this, it has been observed that crowds are complex systems [34, 153, 224]. Studies in the field of evacuation dynamics have shown that people behave different according to the context (normal or emergency situations) [115, 210]. This stresses the importance of a better comprehension of the evacuation process before, during and after an emergency occurs. Together with the possible influence of the location of the occupants in the building at the moment of the evacuation. Thus, this new knowledge permits the adequate estimation of evacuation times and their related processes [197]. Being a definition of risk particular to evacuation dynamics helpful when it is included in the risk management system. In this sense, the definition of risk used here, is considered to be the most useful regarding evacuation dynamics and in especial for the reduction of fatal events.

$$\text{Risk of Fatal Events} = \text{Hazard} \cdot \text{Vulnerability} \cdot \text{Exposure} \tag{2.2}$$

Equation 2.2 shows two main possibilities for the reduction of fatal events within evacuations. The first one regards on the reduction of hazards due to natural and man-made events. Meanwhile, the second suggests the reduction of the vulnerability or the exposure of the occupants of the building at the moment of the emergency.

Some Definitions

For the correct application of the Risk Management Chain (RMC-) Methodology for the reduction of fatal events in evacuation of buildings (Figure 2.2), some definitions regarding the considered system and its elements are necessary. In Figure 2.3 a representation of a generalised building-scenario with several occupants inside and outside is given. The definitions of the system, its elements their initial state and corresponding classification are given as follows.

- **Initial State.** The initial state is considered to be the *"situation"* at the initial time, $t(0) = t_0$.
- **System.** The system is composed by all the occupants of the building to be evacuated. The free space to move and the internal walls with which

rooms are constituted. In the present study emergencies due to explosions are not considered, therefore the characteristics of the building do not change in time or in space.

- **Elements.** Each individual located at the inside the building to be evacuate at time t_0 are considered elements of the system. When two or more elements exhibit similarities they can be divided into *classes of elements*. The present study introduces three types of individuals, in accordance to the physiological characteristics that they present (see Table 6.7).

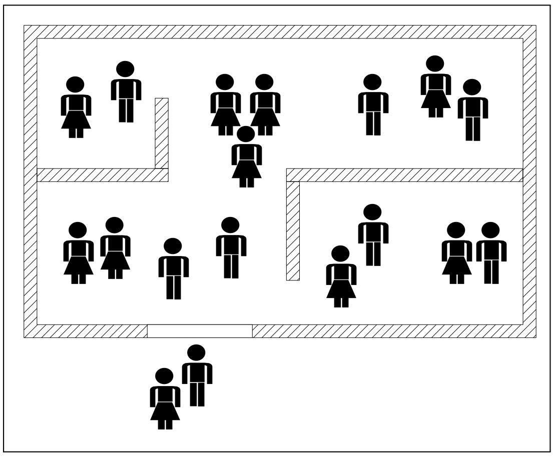

Figure 2.3: Representation of a generalised evacuation-scenario.

- **Elements at Risk, EaR.** At time t_0 all the individuals located inside the building are considered to be at risk, and therefore to be Elements at Risk (EaR). For instance, by following this definition and according to its location, in Figure 2.3 only sixteen individuals of the total eighteen are EaR.

- **Elements at No Risk, EaNR.** So far an individual evacuate the building, then it is considered to be "rescued" and therefore is not at risk (EaNR). Also at time t_0 all the individuals located outside the building are considered as EaNR, and do not take part of the system.

Some Considerations

In the present study it is assumed that all EaR are equally exposed and that exposition is a binary variable (with values of 0 or 1), and is constant in time and in space. So far an individual is located inside a building, it is defined as an EaR with an exposition value of 1. When this individual leaves (evacuates) the building, then it is no longer at risk and therefore is also not exposed (exposition is equal to zero). Variations in exposition values are considered to be outside the focus of the present study. Therefore the definition of risk of fatal events (Equation 2.2) can be simplified into:

$$\text{Risk of Fatal Events} = \text{Hazard} \cdot \text{Vulnerability} \tag{2.3}$$

Where the reduction of fatal events related to evacuation processes now depends on the sources of hazards and the vulnerability of the occupants.

Sources of Hazard

The history of human society shows many examples of fatal accidents regarding to evacuations and collective events [210]. Although each example is unique and not repeatable, sources of hazards that may lead into a fatal incidents are common. In the present study three main sources of hazard are considered: hazards due to the infrastructure, hazards due to the type of initial event and hazards due to the behavioural response of the occupants. In Table 2.2 (Section 2.1.1) the most frequent hazards associated to fatal events were summarised and classified.

In the present work, the potential sources of hazard presented in Table 2.2 will only represent the starting event of an emergency inside a building. But the calculation of its probability of occurrence is not considered part of the study.

2.2.3 Implications to this Study

Calculation and application of evacuation times is a common practise regarding safety in the built environment. However, the available models of calculation do not consider other potential influencing factors of the evacuation process (e.g. behavioural responses and characteristics of the occupants). An alternative solution to safety inside buildings is the application of management methodologies. In the present study the use of a Risk Management Chain Methodology (Figure 2.1) is suggested as an alternative and integral solution to the reduction of fatal events due to evacuation processes. Therefore, risk of fatal events has been defined here and those potentially influencing factors determined (Equation 2.2). The sources of hazards were identified (Table 2.2), but the probability of occurrence is beyond the focus of this study. The same occurs to the determination of exposure, which was previously defined to be equal to every occupant of the building and to be invariant in time. In this sense, the present work focuses in the study of the vulnerability of the occupants of the building and its influence over the evacuation times. For this purpose, a central point in this research is the introduction of simulations of evacuation dynamics as a source of evacuation data.

Chapter 3

Modelling Evacuation Dynamics: State of the Art

The study of evacuation dynamics is a relative new field of increasing interest. First studies in this field were orientated to the efficiency of a building (i.e., design criteria and level-of-service). However, the introduction of the concept of safety in the built environment for the reduction of fatalities due to evacuations lead to the development of several mathematical models. This chapter presents an overview of the actual state-of-the-art regarding the modelling of building evacuation. Section 3.1 gives a general review about the first studies of evacuation dynamics and the characteristic motion patterns. Until now a large number of models describing crowd dynamics (in emergency or normal situations) have been developed under several scopes. However, there are no clear issues for classifying them. Section 3.2 presents a suggested classification based on the level of description of the crowd (micro-, macro-, or mesoscopically), and to the way in which the interactions inside the crowd are understood (engineering, biology, psychology approach). Because of the different approaches and assumptions taken for their development, each model presents diverse capabilities and limitations for the description of evacuation dynamics (as seen in Section 3.3). In this study, the nature of pedestrian dynamics is understood as a self-formation phenomena which presents several interaction rules among the crowd members. Moreover, this work is focused on the development of a new model in which the description of motion should also integrate psychological aspects of evacuation behaviour. For this purpose, Section 3.4 provides an overview of the suggested requirements that any new model for describing evacuation dynamics should fulfil.

3.1 Fundamentals of Evacuation Dynamics

The study of human behaviour is traditionally released to the sociological and humanistic sciences. However, evacuation dynamics and the corresponding behavioural patterns require multidisciplinary understanding. Moreover, a further problematic in the study of evacuations is the lack of information regarding to this field. Moreover, the concept of evacuation is strongly related to emergency situations, in which the term of *panic* is commonly misunderstood. This section summaries the most relevant studies and first findings regarding evacuation dynamics. Together with their common emergent self-formations and behavioural responses.

3.1.1 First Studies on Evacuation Dynamics

The study of human behaviour within evacuations and its dynamics is a relative new field of research with increasing interest from the scientific community, whose early beginnings date back to the late 50's. However, it was by the beginning of the 70's when the study of evacuation dynamics took higher relevance. The first studies of behaviour of individuals within evacuations were close related to the development of evaluation methods in the built-environment. Examples of these are the efficiency of building-designs, design elements for pedestrian facilities [186] or planning guides [80, 192], and the introduction of the so-called level-of-service-concept [79].

Because of the nature of human behaviour, the development of collective behaviour has been typically studied by psychological and social sciences. However, those studies were commonly focused on the description of the phenomena (for instance, by statistical analysis) instead of its reproduction (by means of generalised mathematical models). In this sense, first studies for the description of evacuation dynamics were orientated to the understanding of pedestrian phenomena and were based on direct observations [115]. The recognition of the existence of similitude with mobility patterns (for instance of nomad communities and/or animal behaviour) supposed the basis for the development of the first theories and models explaining pedestrian and evacuation dynamics.

3.1.2 Emergent Self-Formations in Evacuation Dynamics

Human beings (like any other living being) has the natural tendency to form societies and groups [90, 226]. In general, societies are related to complex social structures whose members present similar characteristics (like families) or may share common objectives (e.g. political, sportive, religious). The interaction and grouping among several societies may result in the development of bigger and more complex structures (like cultures or countries) [57]. However in the case of smaller groups or crowds, the complexity of their social structures is lower than in societies. In some cases the formation of groups may be spontaneous or regarded to a specific event. However, a common objective for its formation may not always be present [2]. A starting point in the study of pedestrian dynamics is the introduction of the term *crowd*. A crowd (according to sociologists) is considered as a social system whose behaviour is described on different levels according to the cognitive and social processes which are taking part [224]. A less detailed definition suggests the crowd as a massive concentration of interacting people which may or may not follow a common interest [145, 153, 250]. Beside the nature of the definition, it was found that pedestrian crowds present several behavioural patterns [9, 34, 51, 109, 111, 113, 119, 128, 153, 174, 177, 198, 224, 250], which change according to the situation experienced (for example, by the absence or presence of an emergency or unknown situation) [55, 58, 115, 114, 209, 212].

Studies of behavioural crowd dynamics (based mainly on observations) suggest the presence of certain local behavioural patterns which may result in global behaviours (the so-called self-formations), which leads to the self-organisation of the crowd.

> "***Self-formation*** is a process in which patterns at the global level of a system emerges solely from numerous interactions among the lower level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern."
>
> *Camazine et al. [46], p. 08.*

In general, behavioural patterns of motion are commonly present at almost any biological system (like bacteria, insects, mammals). However most of this self-organisation is regarded to instinctive needs (looking for water or food sources, increase of survival chances) than to a conscious objective. In the case of human beings self-formation patterns are also developed, although the existence of a determined collective objective is not always clear. In especial when the members of the crowd are not closely related to each other. The behavioural patterns regarding pedestrian and evacuation dynamics most commonly referred in the literature are summarised in the following example.

Let us consider the hypothetical case of a group visiting a museum. During the visit (the so-called ***normal situation***) one may observe that:

- Visitors have defined locations of interest (i.e., exhibition rooms), and have a strong aversion to change their walking direction or taking detours [83, 117], but the fastest route is preferred [83], with the predilection of walking at a comfortable speed [120, 192, 258].
- A certain distance among each visitant is kept [21, 28].
- And in attractive places, higher and increasing densities may be observed and people which are familiar or related to others tend to form groups [107, 109].

However with the occurrence of an unexpected event, persons tend to organise themselves in a different way. For example, the presence of a fire alarm during the group visit to the museum may represent an ***emergency situation***. However not all emergency situations are taken as real (in a first instance) and persons may behave as being done in normal situations. In the case that the emergency scales, the behavioural pattern of the visitors would change into what is considered to be *panic*. In the so-called ***panic-scaled situations***, visitors may then intend:

- To increase the desired walking speed as a first response to the alarm [192]. Meanwhile, the emergency exits are the main goal to achieve.
- The appearance of the so-called *"blind actionism"* due to nervousness [115] and physical interaction (by means of pushing) among the individuals [67, 227] may be present.
- Moreover, herding behaviour [137, 198] and changes on the original (or predefined) evacuation plan by unplanned events (locked doors) or ignorance of existing emergency exits may occur [67, 137].

An early assumption regarding self-formations was that those patterns were formed simultaneously or with no apparent dependency to the type of situation [153]. However recent studies suggest those formations as inherent to pedestrian dynamics [58, 117, 119, 209] and even some of them (i.e., in-coordination of movement in bottlenecks [177], formation of arches and clogs at exits [192]) keep similarities with particle dynamics when seen as a global behavioural pattern [115]. Based on those analogies, further pedestrian phenomena were recognised (i.e., “freezing by heating”[232], “faster is slower effect”[115], lane formations and oscillations at bottlenecks [210]) and are still under study [58, 114, 209, 212].

3.2 Available Models for Evacuation Dynamics

A *crowd* is commonly seen as a group of individuals with apparently no common goal, but with the presence of interactions among its members [153, 161, 223]. When an emergency occurs those goals change and the resulting behaviour may escalate into violence or panic [224, 226]. In evacuation of buildings crowds are always involved, and therefore a major understanding of the interactions among its members is crucial. Until now many models describing crowd dynamics have been developed under several scopes [44]. But many questions regarding the simulated behaviour of crowds and their validity into real situations are still unclear [223].

Pedestrian dynamics is a field with growing interest with an increasing number of models for its description. Until now, there are no clear issues for classifying the existing models for pedestrian dynamics. However in the present work, a general classification is suggested. For classifying a model two criteria were taken: first the way in which the studied crowd is defined (that is, by its single elements or as a complete entity) and second the nature of the description of the interactions inside the crowd. Based on these criteria, the available models for describing pedestrian phenomena are categorised in engineering-based, psychology-based and biology-based (Figure 3.1). The macro-, meso-, and microscopic subcategories correspond to the level in which the crowd system is described.

Engineering-based models assume that interactions within a crowd are ruled by physical-like laws. In other words, the individuals are considered to be dynamic objects (absent of "thinking-properties"), whose behaviour is suspected under physical laws (like in fluid dynamics or force fields) [110, 119, 124, 214]. The psychology-based models, in contrast, assume that pedestrian interactions are ruled by socio-psychological processes. This means, that the individuals are entities who can think and behave according to the situation [223]. Thus, crowd dynamics are the result of the perceived surrounding environment [134, 256]. Finally, the biology-based models suggest the process of self-organisation (given in several biological systems) as a manner for describing crowd dynamics.

In addition to this, the engineering approach suggest two different strategies for simulating the crowd behaviour. These strategies are referred to the manner how the crowd system is defined. In the macroscopic definition, the

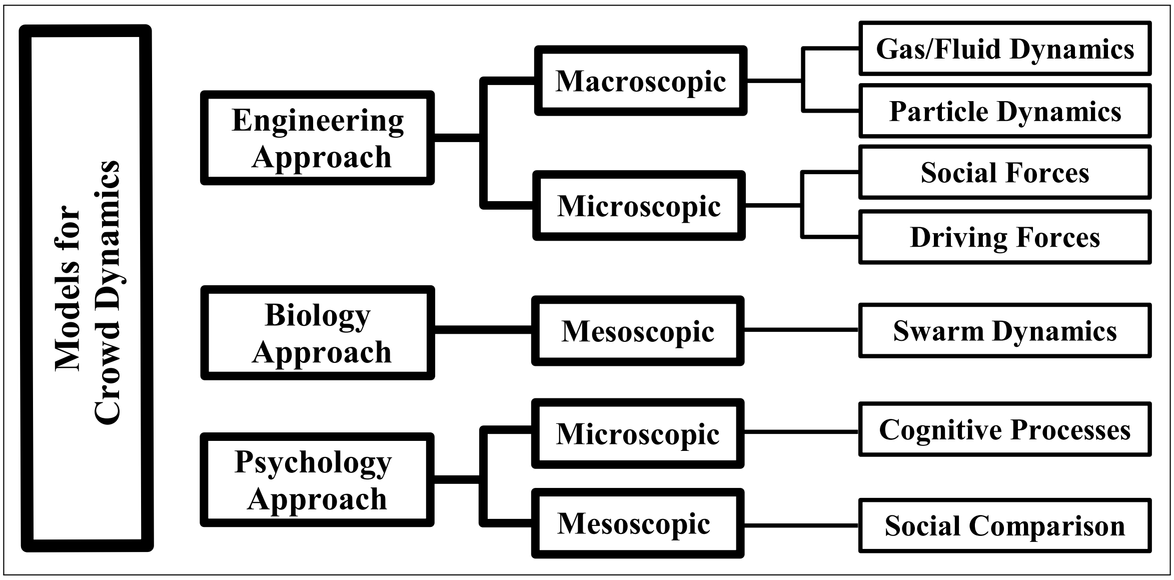

Figure 3.1: Classification of those available models for crowd dynamics, as suggested in [131].

crowd is assumed as a continuous and homogeneous substance-like whose behaviour keep close similarity to fluid or particle dynamics and no distinction between individuals is modelled. In this sense, modified Lattice-Boltzmann, gas-kinetic, Navier-Stokes and Traffic-like equations are frequently referred [21, 24, 48, 59, 79, 80, 103, 107, 108, 110, 112, 120, 121, 210, 213, 259]. Based on the microscopic definition, the crowd is considered to be a discrete material influenced by physical forces (like potential and dynamic fields) [42, 93, 100, 116, 117, 119, 142, 151, 159, 162, 206, 210, 214, 232]. A force-alike-model, the Social Force Model of Helbing [109, 118] and its later modifications [27, 162, 206, 214, 232, 257] is one of the most representative model for describing pedestrian behaviour, under the microscopic definition of a crowd.

On the other hand, the psychological approach supposes that crowd behaviour is the result of specific cognitive (mental) and comparison processes according to the situation which the involved individuals are experiencing [86, 87]. Visual perception is frequently referred as the mental process with which the individuals obtain information of its surroundings [88, 89, 175, 203, 205]. This leads to several visual-perception-based models [203, 205]. However a mathematical model describing evacuation dynamics based on visual perception has not been suggested until now.

The biological approach, considers a mesoscopic definition of the crowd. In general words, a mesoscopic model can be seen as an interphase between the macro- and microscopic approaches. Thus, the interactions among pedestrians (microscopic definition) and their effect in the global behaviour (macroscopic definition) are taken into account. Moreover, the nature of the interactions on the microscopic level are assumed to keep a close relation to those given in certain biological systems (i.e, swarms and several colonies of insects). A commonly referred model based on these assumptions is the work of Reynolds [200]. Examples of mesoscopic models are given in the field of way-finding in robotics [19, 20, 68, 211, 234] with applications in dynamics [95, 96, 97, 150].

The discovery of self-formation patterns played an important role for the foundation of *evacuation dynamics*, and their later model formulations [159, 162, 206]. In this section a review of the foundations, main assumptions and the corresponding capabilities and limitations of the most relevant models for describing pedestrian and evacuation dynamics (shown in Figure 3.1) is given. In addition, Table 3.1 shows a general comparison of the models based on the manner in which self-formations in evacuation dynamics are assumed and modelled.

Approach	Description Level	System Elements	Interaction Rules
Engineering	Macroscopic	Crowd	Fluid Dynamics
			Probabilistic Distribution
	Microscopic	Individual	*"Social"* Forces
			Force Fields
Biology	Mesoscopic	Crowd / Individual	Self-organisation
Psychology	Microscopic	Individual	Cognitive Processes
	Mesoscopic	Crowd / Individual	Comparison

Table 3.1: Comparison between system definitions and interaction rules within those available models for crowd dynamics.

According to the definition of self-formation suggested by Camazine et al. [46], the description of self-formation paths requires two main ingredients: the elements of the system and the rules of interaction among them. In first place the level of description of evacuation dynamics defines the elements of the system. However, the scale of description is independent to the assumed nature of the upcoming interactions (engineering-, psychology- or biology-based) but not in the other way around. For instance, pedestrian dynamics in evacuations may be described by considering the crowd as the unique element of the system (macroscopic level) or by considering each individual as single elements of the whole system (microscopic level). An especial level of description is the mesoscopic, in which the crowd and the individuals are considered both as system elements and the interactions taking place are described globally (when the crowd is the single element) or locally when each single individual is considered. Then, the interaction rules among the elements of the system are defined in accordance to the level in which the system has been described. For instance, in the macroscopic level, self-formation is given by a defined interaction rule affecting the system globally (for example, fluid or particle dynamics). Opposite to this occurs with the microscopic level, where the rules of interactions actuate locally.

3.2.1 Engineering Approach

Interactions taking place in pedestrian dynamics and during evacuation processes are assumed to keep a strong relation with physical laws of motion (classical mechanics) or to be the effect of a certain force. However the description of behavioural motion patterns in pedestrian groups is not limited to the description of the nature of the interactions taking place, therefore the inherent characteristics of the participating members of the crowd must be also considered. In this sense, the engineering approach suggest two strategies for simulating the crowd behaviour. These strategies are referred to the manner how crowd is defined, and in accordance to the corresponding upcoming-interactions among its members. For instance, in the macroscopic definition the crowd is considered as a continuous and homogeneous *"substance"* whose behavioural patterns keep close similarity to fluid or particle dynamics. In the microscopic definition the crowd is considered as a type of *"material"* constituted by a defined and recognisable number of elements whose interactions are influenced by physical forces (i.e., potential and dynamic fields).

Macroscopic Approach

In the macroscopic approach the study of pedestrian and evacuation dynamics tends to the homogenisation of the characteristics of the crowd and a generalisation of the nature of the upcoming interactions inside it. Behavioural dynamics described by the complete crowd are taken as average values, since no distinction among its members (individuals) is made [108, 110]. The same occur with the description of the interactions inside the crowd. They are assumed to keep certain similarity with fluid or particle dynamics by considering to be continuous and with large number of individuals [9, 132, 253]. In this sense models based on Lattice-Boltzmann, H-theorem and Navier-Stokes have been developed but with certain corrections. In particular those related to collision avoidance, deceleration manoeuvres (common in pedestrian crowds) and the fact that pedestrian crowds do not conserve momentum and energy, as unanimated material does [119]. In general, the basis of macroscopic models is the *continuity equation* which presents the relation between density and flow of the crowd [144]. This was empirically shown in the so-called *fundamental diagram* [103, 113, 108]. One of the first applications of the macroscopic approach was the traffic simulation which later asset the basis for the modelling of pedestrian dynamics [21, 79, 80].

Classical Lattice-Boltzmann. The Lattice-Boltzmann Model (LBM) is a particle-based model, in which collisions, streaming, and interactions of type particle-particle or particle-surface constitute the general concept [239]. The LBM for gas components supposes that gases are composed by large numbers of interacting particles whose interactions can be described by classical mechanics (mass and momentum conservation are assumed to be fulfilled). However in the limit of the large number of particles ($N_A = 1 \times 10^{23}$ particles/mol of gas) the motion description of the particles is done statistically by means of single-particle distributions $\left(f^{(1)}(\boldsymbol{x}, \boldsymbol{p}, t)\right)$ [238, 239].

In the classical concept of Lattice-Boltzmann the study of motion is done by the discretisation of the domain into regular lattices. At each lattice site exist a single-particle distribution. This distribution function is equal to the expected number of particles in each of the available i particle states. In the simplest case, to each particle state i corresponds a particle velocity. On each discrete time step, the particle is allowed to move to the nearest lattice site along its defined direction of motion. The arrival of diverse particles to a same site is possible and a collision between them may take place. Producing, in this way, a new particle distribution. This new particle distribution can be determined by solving the kinetic (Boltzmann) equation.

Boltzmann's Kinetic Theory. For the development of Boltzmann particle distribution function the following considerations are to be taken:

- The stream under study is a dilute gas consisting of N-interacting hard and spherical particles moving at high velocities,
- Only elastic collisions (structureless molecules interacting via a short-range 2-body potential, whose total kinetic energy stays constant before and after the collision) among the particles are present,

- Since there is no distinction among the particles constituting the gas stream the complete N-particle system is represented by an ensemble of many copies of a single-particle ($N = 1$), this means that the new particle distribution $f^{(1)}(\boldsymbol{x}, \boldsymbol{p}, t)$ can be obtained without specifying the other $N - 1$ particles.

In general the gas-kinetic equation for one-body distribution function is represented as follows:

$$D_t f^{(1)} \equiv \left[\partial_t + \frac{\boldsymbol{p}}{m}\cdot \partial_{\boldsymbol{x}} + \boldsymbol{F}\cdot \partial_{\boldsymbol{p}}\right] f^{(1)}(\boldsymbol{x}, \boldsymbol{p}, t) = C_{12} \tag{3.1}$$

The left side of Equation 3.1 represents the streaming motion of the particles described by their trajectories, which at the same time are associated with the force-field $\boldsymbol{F}$ (conservation of momentum $\boldsymbol{p}$ in any position $\boldsymbol{x}$) at any time t. In the right side of the equation, C_{12} represents the particles which do not arrive to the expected position due to the effect of intramolecular (two-particle) collisions.

In the case of dilute gases, collisions among the particles are rare and in absence of external fields, particle-interactions can be described in terms of localised binary collisions. This approximation is called the *Stosszahlansatz* or *molecular chaos*. Mathematically this closure assumption is expressed as:

$$f_{12} = f_1 f_2 \tag{3.2}$$

The Stosszahlansatz assumes that there are no correlations between the particles entering in a collision. Therefore the velocities of colliding particles are uncorrelated and independent to the position [238, 239].

Adaptation of LBM to Pedestrian Dynamics. The general concept of motion description of particles given by the LBM was used by several scientist for the description (in the limit of large numbers of particles) of the macroscopic motion of pedestrians but with some modifications [107, 108, 110, 112]. Some of the modifications were suggested by Helbing by considering the similarities to fluid streamlines on observed footprints left by pedestrian crowds in the snow or quick-motion pictures, but without considering mass and momentum conservation [120, 121]. Further modifications to the traditional LBM are the introduction of some additional terms (like the tendency of pedestrian to walk with an intended walking velocity ($\boldsymbol{v}^0$) or the changes in the direction of motion (μ, ν) due to avoiding manoeuvres or collisions).

In general the continuity equation describing the changes of pedestrian motion proposed in [107] has the form:

$$\frac{d\hat{\rho}_\mu}{dt} \equiv \frac{\partial\hat{\rho}_\mu}{\partial t} + \nabla_{\boldsymbol{x}}(\hat{\rho}_\mu \boldsymbol{v}_\mu) + \nabla_{\boldsymbol{v}_\mu}\left(\hat{\rho}_\mu \frac{\boldsymbol{f}_\mu}{m_\mu}\right) + \nabla_{\boldsymbol{v}_\mu^0}\left(\hat{\rho}_\mu \dot{\boldsymbol{v}}_\mu^0\right) \tag{3.3}$$

in which $\hat{\rho}_\mu(\boldsymbol{x}, \boldsymbol{v}_\mu, \boldsymbol{v}_\mu^0, t)$ describes the number of pedestrians N_μ describing the motion type μ localised within an area $A = A(\boldsymbol{x})$ and having approximately the intended velocity $(\boldsymbol{v}_\mu^0)$, but describing approximately the actual velocity $(\boldsymbol{v}_\mu)$. The term (m_μ) is the average mass of pedestrians describing the motion type (μ) (and is assumed to be approximately equal to the mass of pedestrians describing any other type of motion).

Then, Equation3.3 suggests that the changes in the density of pedestrians $\hat{\rho}_\mu$ are given due to four effects:

1. The effect about the tendency of pedestrians to reach their intended velocity $(\boldsymbol{v}_\mu^0)$, which leads into an equilibrium density $(\hat{\rho}_\mu^0)$ in an relaxation time τ_μ.

2. The effect of paired interactions $\hat{S}_{\mu\nu}$ among the pedestrians μ and ν, as suggested by the Stosszahl-ansatz in the traditional LBM.

3. The effect of the change in the original motion type $\hat{C}_{\mu\nu}$ described by the pedestrians.

4. The effect of density gain $\hat{q}_\mu^+\left(\boldsymbol{x}, \boldsymbol{v}_\mu, \boldsymbol{v}_\mu^0, t\right)$ or density loss $\hat{q}_\mu^-\left(\boldsymbol{x}, \boldsymbol{v}_\mu, \boldsymbol{v}_\mu^0, t\right)$ per time unit caused when pedestrians leave the system under study (by evacuating a building).

Then by integrating these four effects, Equation 3.3 can be alternatively written as:

$$\frac{d\hat{\rho}_\mu}{dt} := \frac{\hat{\rho}_\mu^0 - \hat{\rho}_\mu}{\tau_\mu} + \sum_\nu \hat{S}_{\mu\nu} + \sum_\nu \hat{C}_{\mu\nu} + \hat{q}_\mu \tag{3.4}$$

Both Equations 3.3 and 3.4 describes the same probability distribution of pedestrians based in the traditional idea of lattice Boltzmann for gaseous components. However for the case of pedestrian dynamics, the fulfilment of mass and momentum conservation is not strictly achieved as in the case of gases. Therefore, the following assumptions should be additionally considered:

1. Conservation of momentum and energy is assumed to be fulfilled in the case where pedestrians adjust their actual walking velocities into the intended one within a relaxation time (τ_μ).

2. Mass conservation takes place in those cases in which a size distinction among pedestrians groups of any motion type is not possible $(m_\mu \approx m_\nu)$. This means that pedestrians may change their motion type and new pedestrian groups may be formed, however the size of the new groups tends to be constant with respect to the size of the previous ones.

The H-Theorem for Fluid Dynamics. According to the Second Law of Thermodynamics, the most probable state of a closed system in equilibrium is the one which presents the maximal entropy (H). In other words, the entropy measures the temporal irreversibility (the so-called degree of disorder of the molecules conforming a fluid) of the system. Entropy is defined as:

$$H(t) = -\int f \ln f d\boldsymbol{v} d\boldsymbol{x} \tag{3.5}$$

The entropy of a closed system will increase in time until it achieves an asymptote (the equilibrium state), as seen in Equation 3.6. Once the system has arrived the equilibrium, the entropy would not decrease, except in the case of local fluctuations caused by thermal noise (changes in the direction of movement) of the molecules of the fluid.

$$\frac{dH}{dt} \geq 0 \tag{3.6}$$

The H-Theorem for Pedestrian Dynamics. In general the lattice Boltzmann-like models provides a probabilistic description of pedestrian distributions. The pedestrian distributions change in time, and may differ from one crowd to another according to its characteristics. The changes in time of the distributions is commonly measured in terms of entropy (Equation 3.6), which describes the *"degree of order"* experienced in a system. According to this thermodynamical law, the most probable state of a isolated system is that one which exhibits a maximal disorder (equilibrium state). In other words and for the case of evacuation dynamics, the thermodynamical law states that independent to the nature of the crowd, after a certain time an stationary state (or equilibrium) in the distribution would be reached.

Traditional Fluid Dynamic Equations. The general idea behind traditional fluid mechanics is the description of the motion of a fluid medium (liquid or gas) in time by considering that mass, momentum and energy are conserved. However, for the achievement of this goal the fluid medium shall be assumed as a continuum and without distinction among its elements.

> "***Continuum*** is assumed to consist of very small volume elements, the overall dimensions of which, however, being much larger than the intermolecular distances."
>
> *E. Krause. [148], p. 01.*

Since the fluid is considered to have a homogeneous nature, the system is then described by the mean values. For instance, the system variables: velocity, pressure, temperature and density. Together with the fluid properties: like viscosity, thermal conductivity and specific heat. Both, the system variables and the properties of the fluid are space and time dependent.

Conservation of Mass. The equation for mass conservation describes the changes in motion of a fluid with mass (m) contained in a closed volume, in which the mass remains constant in time (no further incomes or outcomes of mass in the volume are possible). The dynamics of the fluid in motion is then described by the changes in time and position of the density (ρ) and velocity $(\boldsymbol{v})$. Mass conservation, when the system is in equilibrium, is commonly expressed as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \tag{3.7}$$

Conservation of Momentum: – The Navier-Stokes Equation. The general concept of the momentum theorem is the description of the changes of momentum experienced by a flow in motion in a closed system. This momentum rate is given by the effect of the gravitational force acting on the fluid and the forces at its surface (which allow or avoid the fluid to flow). This description of momentum change is known as the Navier-Stokes (Equation 3.8), in which $(\boldsymbol{g})$ is the vector of gravitational acceleration and $(\bar{\bar{\sigma}})$ the stress tensor.

$$\rho \left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\, \boldsymbol{v} \right] = \rho \boldsymbol{g} - (\nabla \cdot \bar{\bar{\sigma}}) \tag{3.8}$$

Conservation of Energy. The Bernoulli Equation describes the change rate of energy in a closed system with an incompressible and loss-free fluid in motion inside of it. With mechanical energies (internal (ρe) and kinetic energy $(\frac{1}{2}\rho \boldsymbol{v}^2)$) acting over the fluid. However in the case in which the fluid under study has large density or experiences changes in temperature, the properties of the fluid and its dynamics change. For instance, by considering the existence of heat conduction $(\lambda \nabla T)$, a change of the thermal energy must be considered.

In this sense, other forces (volume $(\rho\,(\boldsymbol{g}\cdot\boldsymbol{v}))$, pressure $(\nabla\cdot(p\boldsymbol{v}))$ and friction $(\nabla\cdot(\bar{\bar{\sigma}}'\cdot\boldsymbol{v}))$ forces) act on the fluid. In general the change in time of the total energy acting on a fluid contained in a closed volume is expressed in the following way:

$$\rho\frac{d}{dt}\left(e+\frac{\boldsymbol{v}^2}{2}\right)=\rho\,(\boldsymbol{g}\cdot\boldsymbol{v})-\nabla\cdot(p\boldsymbol{v})+\nabla\cdot(\lambda\nabla T)-\nabla\cdot(\bar{\bar{\sigma}}'\cdot\boldsymbol{v}) \tag{3.9}$$

Modifications of the Traditional Fluid Dynamic Equations for Pedestrian Dynamics. First formulations of models describing evacuation dynamics were originally based in gas-kinetic theory [120, 121] (as seen earlier in this section). The approach compares large crowds with classical gases, and assumes analogous behaviour. Interactions among pedestrians are described as collisions, in which momentum and energy is exchanged, but the total amount is conserved. For instance, by assuming a closed system, where no persons are allowed to entry or to leave the studied building. In order words, pedestrian dynamics are described by the local changes in density and the walking speed.

However and due to the nature of human behaviour, the assumption of momentum and energy conservation are difficult to satisfy. In this sense, further works describing pedestrian dynamics avoided conservative approaches and considered other factors influencing the dynamical behaviour. For instance, the existence of a preferred and individual direction of motion [107]. With the introduction of this new property of the observed crowd, Helbing (in [107]) distinguished different groups of pedestrians based on the type of motion (μ) that they describe. Then, the temporal changes in the local density $(\hat{\rho}_\mu)$ of pedestrians with motion (μ) (Equation 3.4) are assumed to be influenced by four different effects:

1. The tendency to reach the intended velocity $(\boldsymbol{v}_\mu^0)$ in a characteristic time (the so-called relaxation time, τ_μ).

2. Interactions among pedestrians are of the type described in Equation 3.2, where the rate of collisions is proportional to the amount of pedestrians with motion (μ) and (ν).

3. The change of type of motion (for instance, μ and ν).

4. and by considering that in any situation, pedestrians are allowed to entry or to leave the building (the studied system).

Moreover, the approach proposed by Hughes suggested further assumptions [123, 124, 125, 154]. Here, the influence of the direction of motion of the pedestrians in the global dynamics of the crowd is neglected. In this sense, Hughes arrives to three hypothetical factors affecting the motion of the crowd:

i) The walking speed of the observed pedestrian is determined by the amount of pedestrians (density) in its vicinity, their behavioural characteristics and the direction of walk.

ii) Pedestrians know their intended destination, which functions as a type of potential (ϕ).

iii) Pedestrians tend to minimise the estimated travel time by avoiding extreme densities. This is referred as a *discomfort-factor*.

The governing equation of pedestrian flow, according to Hughes has then the form:

$$\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial \boldsymbol{x}} \left(\rho \boldsymbol{g}(\rho) \boldsymbol{f}^2(\rho) \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{x}} \right) + \frac{\partial}{\partial \boldsymbol{y}} \left(\rho \boldsymbol{g}(\rho) \boldsymbol{f}^2(\rho) \frac{\partial \boldsymbol{\phi}}{\partial \boldsymbol{y}} \right) \tag{3.10}$$

with

$$\boldsymbol{g}(\rho) \boldsymbol{f}(\rho) = \frac{1}{\sqrt{(\frac{\partial \phi}{\partial \boldsymbol{x}})^2 + (\frac{\partial \phi}{\partial \boldsymbol{y}})^2}} \tag{3.11}$$

However, a common problem in models based on gas-kinetic and fluid dynamic theories is with regards to the case of low and high densities [124, 209].

Traffic Approach and Pedestrian Dynamics. Short after the invention of automobile, transportation problems appeared. The increment of people able to own a car and the opening of frontiers between countries (e.g. commercial treatments) favoured the terrestrial transport and converted it into a common tool for mobility. This situation made the problem more acute and opened new research. In this sense, the study of traffic phenomena opened the possibility to the eventual decision-making based on a better understanding of the phenomena (i.e., manners to alleviate congestion, maximise flow of traffic, eliminate accidents and minimise automobile exhaust pollution). The traditional approach to traffic modelling is based on observations and assumed similarities to fluid dynamics [103]. However, the study of traffic assented the basis to the study of more complex systems, like pedestrian dynamics. In this sense, the development of the so-called *fundamental diagram* (an empirical relationship between density and flow) for traffic and for pedestrian dynamics

[209, 212, 213, 214]. In other words, the description of traffic dynamics is achieved by means of its fundamental variables: *velocity field, traffic flow* and *traffic density*. A similar description for pedestrian dynamics is also referred to the measurement of these variables [228]. In this sense, early studies regarding evacuation dynamics and design strategies for safety inside buildings considered the relationship among pedestrian density, its walking velocity and its flow [72, 186, 209]. Regarding to pedestrian dynamics, the use and development of the fundamental diagram is known as the *hydraulic model* and it has been widely referred for the calculation of evacuation times (Section 2.1.2).

The so-called *conservation law* for traffic is expressed as:

$$\frac{\partial \rho(\boldsymbol{x}, t)}{\partial t} + \frac{\partial}{\partial \boldsymbol{x}}[q(\boldsymbol{x}, t)] = 0 \tag{3.12}$$

this equation describes the relationship between traffic density (ρ) and traffic flow ($q(\boldsymbol{x}, t)$) derived by assuming that the number of cars is conserved, and it is valid everywhere (all $\boldsymbol{x}$) and for all time. Considering that traffic flow relates density and velocity:

$$q(\boldsymbol{x}, t) = \rho(\boldsymbol{x}, t)\boldsymbol{v}(\boldsymbol{x}, t) \tag{3.13}$$

then we have that Equation 3.12 is the same as the traditional equation for mass conservation (Equation 3.7) and keeps similarity to the macroscopic description of pedestrian dynamics. The present chapter is intended to give an overview of the available models regarding pedestrian dynamics. Thus, further improvements and modifications to traffic models are not shown here. Good references in this field are the works of Helbing [108, 113] and Darbha et al. [59].

Microscopic Approach

In the microscopic approach, the crowd is described from its lower level. In other words, behavioural dynamics of a crowd are described by considering each individual and the behaviour that it presents. In this sense, big concentrations of people (or pedestrian crowds) are modelled by discretising the crowd into its basic components (as seen in Table 3.1). In the microscopic approach each element of the crowd can be individually characterised by a set of parameters (like age, walking speed and gender). However, depending on the assumptions taken, individuals can be grouped when common characteristics (like relatives or a handicap) are present. Moreover, the discretisation of the crowd permits a higher level of description of the interactions taking place in the crowd. In general terms, the interactions among a crowd inside a building are of the type: individual-individual, individual-other individuals and individual-building [145], and not an averaged interaction as proposed in macroscopic models. Then these individual interactions may be described as the result of external driving forces acting on each person. An example of these driving forces are the so-called *social forces* [118]. The social forces describe the interaction of attraction or repulsion between individuals. The use of force (like potential) fields [100, 159] or the tracking of an specific path (like in chemotaxis) [142] are alternative forms for describing the interactions among pedestrians. A common computational technique used in microscopic models is the cellular automaton (CA) or cellular automata (in plural). A good reference for reviewing the foundations of its definition and properties is the book written by Weimar [260]. However, a brief explanation of CA is given in this section.

Cellular Automaton for Describing Pedestrian Dynamics. A cellular automaton (CA) is a regular array of lattices (cells) with a finite number of states [260]. The CA can be also seen as a finite-state-machine, in which the state of a cell will change in each time step [182]. For this, time discretisation is needed. The change of state is given by defined evolution rules (also called as transition rules). However, states are also influenced by the previous state and the states experienced by the neighbour cells. Because of its easiness of application, CA has been widely used for describing the evolution of discrete systems with homogeneous interactions [1, 173, 259, 267]. In [260] CA has been formally defined as follows.

Let: $\mathcal{L}$ be a regular lattice with cells as elements, $\mathcal{S}$ a finite set of states, $\mathcal{N}$ a finite set of neighbourhoods (of size $n = \mid \mathcal{N} \mid$) such that:

$$\begin{array}{c} \forall c \in \mathcal{N}, \forall \mathrm{r} \in \mathcal{L} \colon \mathrm{r} + \mathrm{c} \in \mathcal{L}, \\ \mathrm{f} \colon \mathcal{S}^n \rightarrow \mathcal{S} \quad \text{a transition function.} \end{array}$$

Then, the 4-tuple

$$(\mathcal{L}, \mathcal{S}, \mathcal{N}, \mathrm{f}) \tag{3.14}$$

is called a *cellular automaton*. From its definition it can be said that a CA fulfils the following properties: each cell is regular, discrete and is surrounded by a local and uniform neighbourhood. Moreover, cells are characterised by a state and the change of a state (evolution) is given in discrete time steps, but every cell has the same transition rule.

In general, a CA can be constructed by specifying the *geometry* of the lattice (triangular, square or hexagonal), the size of its *neighbourhood* (von Neumann, Moore or any arbitrary type), the initial and boundary *conditions*, the set of possible *states* (a finite number) and their *transition rules*. The transition rules can be defined as: direct, totalistic, implicit, multi-step, as small changes or in a probabilistic way.

One dimensional CA are commonly used for traffic simulations [113, 266]. In the case of pedestrian dynamics, a two-dimensional description is needed. Some examples of their application are shown in [42, 64, 65, 142, 144, 208]. However, pedestrian dynamics presents a higher level of complexity (like “short-time” acceleration manoeuvres and changes of direction) which are not given in traffic dynamics and have to be considered in the transition rules. Together with this, discretisation techniques shows to influence the description of the evolution of the states [140], representing a certain disadvantage in comparison to continuous models for pedestrian dynamics.

The *“Social”* Force Model. The social force (a continuous model) describes pedestrian dynamics based on the interactions among the individuals of a crowd. According to Helbing [118], any individual has a desired destination (direction) to achieve. And the existence of “other” pedestrians or objects influences the direction taken by the observed person. This influences are of type attractive (when the other person or object is of interest or familiar to the individual), otherwise the influence will be repulsive. These attraction-repulsion forces are referred as the “social forces”.

In general terms, the action of the social forces acting over a pedestrian (α) are expressed as:

$$\frac{d\boldsymbol{\omega}_\alpha}{dt} := \boldsymbol{F}_\alpha(t) + \text{fluctuations} \tag{3.15}$$

where $\boldsymbol{\omega}_\alpha$ is the vector of walking speed described by pedestrian (α) and $\boldsymbol{F}_\alpha$ is the effect of all the (social) forces, in a vectorial form, acting over the observed pedestrian. Then, Equation 3.15 is the general form of the *social force model* and it describes the change of the walking direction in time affected by the attractive-repulsive forces ($\boldsymbol{F}_\alpha$) of its surroundings. However, random variations in the behaviour of the observed pedestrian should be considered (here expressed as fluctuations). In general

$$\boldsymbol{F}_\alpha(t) := \boldsymbol{F}_\alpha^0 + \sum_\beta \boldsymbol{F}_{\alpha\beta} + \sum_B \boldsymbol{F}_{\alpha B} + \sum_i \boldsymbol{F}_{\alpha i} \tag{3.16}$$

being $\boldsymbol{F}_\alpha^0$ the effect of the change in time between the desired and actual walking speed of the pedestrian. This time of change (commonly referred as the relaxation time in macroscopic models) is assumed to be very small. $\boldsymbol{F}_{\alpha\beta}$ is the attractive (or repulsive) influence of a pedestrian (β) over the observed pedestrian (α). Analogous expressions for the influence given by a determined object (B) or place (i) are $\boldsymbol{F}_{\alpha B}$ and $\boldsymbol{F}_{\alpha i}$ respectively.

With the introduction of the social force model, several motion patterns observed in pedestrian dynamics (seen in Section 3.1.2) were able to be simulated and studied [114, 116, 118, 119, 162, 232]. However, further studies in pedestrian dynamics and comparisons with experimental data suggested further modifications [214]. In this direction, further assumptions and modifications to the original model have been suggested [116, 117, 119, 162, 206, 210, 232]. Nevertheless, the social force model is under discussion, where the validity of the assumption taken by describing personal wills of movement as an effect of attractive-repulsive forces (like those acting over unanimated objects) is still an open question [209].

Models Based on Driving Forces. An alternative form for describing pedestrian motion is based on the assumption that motion is effected by several driving forces (like potential fields) [159]. Furthermore, Kirchner et. al. [142] suggested a more deterministic way of describing pedestrian motion, and according to them, pedestrians tend to follow a defined pathway (as it occurs in chemotaxis). A further approach for pedestrian movement (a probabilistic one) was suggested by Burstedde et al. [42], where the next most probable position of the observed pedestrian is determined by a so-called matrix of preferences.

Pedestrian Motion as a Result of Potentials. Potential in particle dynamics is commonly described as a particularity of Newton's law of motion. In general the potential gradient is expressed as:

$$m_i \frac{d^2 \boldsymbol{x}_i}{dt^2} = \nabla_i \boldsymbol{\Phi} \tag{3.17}$$

for $i = 1, ..., N$ and being m_i he mass of the i^{th} particle. Here is important to notice, that Equation (3.17) is similar to the description given by the social force model (Equation 3.15), where the *"force of movement"* is obtained from the gradient of the potential function $\boldsymbol{\Phi}$. In accordance to Greengard [100], a typical configuration of a potential field (in particle dynamics) has the form:

$$\boldsymbol{\Phi} = \boldsymbol{\Phi}_{\text{near}} + \boldsymbol{\Phi}_{\text{external}} + \boldsymbol{\Phi}_{\text{far}} \tag{3.18}$$

where $\boldsymbol{\Phi}_{\text{near}}$ represents a rapidly decay of the potential with respect to the distance, $\boldsymbol{\Phi}_{\text{external}}$ is the decay function of an external potential which is assumed to be independent of the number of particles and Φ_{far} is the far-field potential. Once again, the expressed function Φ (Equation 3.18) keeps similarity to the gradient of *"social forces"* acting over the observed pedestrian (Equation 3.16), which at the same time expresses the degree of the so called *"walkability"* of the field [93]. Moreover, potential decay (or increment) varies in function to the distance of other pedestrians (and objects) with respect to the observed pedestrian. More specific, Φ_{near} expresses the effect over pedestrian interactions because of the close vicinity of other pedestrians or objects (similarly expressed by $\boldsymbol{F}_{\alpha}^{0}$, in Equation 3.16). In the same way, Φ_{external}, shows the decay of the potential by considering the interactions between pedestrian and other pedestrians and obstacles occurring in a so-called external neighbourhood (in a similar way occurs with $\boldsymbol{F}_{\alpha\beta}$, $\boldsymbol{F}_{\alpha B}$ and $\boldsymbol{F}_{\alpha i}$). Finally Φ_{far} refers to the interactions between pedestrians and a so-called *"far"* scenario, which has a *"smoothing effect"* over the global movement (of pedestrians, in our case) [100].

Examples of the use of a potential-based model can be reviewed in [93] and [159]. CA methodology is used in both works, where space and time are discretised into square cells. The term *potential* is understood as the possibility of the pedestrian (or the defined amount of pedestrians contained in a cell) to move to another unoccupied cell. Moreover, the use of further algorithms (like flooding) optimises the calculation times, by updating only defined cells (for instance, those ones not being blocked by an obstacle). The use of optimisation techniques (like utility maximisation-based models) allows *"more intelligent"* path-findings by defining a preferred route towards regions of minimal potential (that is, regions with higher level of unocuppied cells). In both works, real-like motion paths were reproduced by relatively simple local transition rules. However the uses of CA also presents some limitations. An example of this, is that motion description has a strong relation to the definition of the neighbourhood (size and shape). For instance a 8-cell neighbourhood yield to zig-zag motion paths, this pattern tends to vanish when the size of the neighbourhood is incremented [93]. Time calculations with CA are relatively short, but it increments strongly by adding the number of simulated pedestrians (O(N^2)). Thus, further optimisation algorithms are required in order to decrease calculation times, specially with large number of pedestrians.

Preferred and Most Probable Position. A further model for describing pedestrian dynamics assumes the existence of a predetermined (or preferred) motion path that is followed by the individuals. This assumption is based on the biological principle called *chemotaxis*. Examples of its implementation (by means of CA) are given in [141, 142]. In their work, Kirchner et al. defines two fields of information, one containing the information about the area to be evacuated, like number of obstacles and emergency doors, as well as their location. This field is called *static field*, since it is time independent. The second field (the *dynamic field*) contains the information of current positions of the pedestrians and their trace left on their way to the exit. The dynamic field (as it names said) is time dependent and the state of the field is altered by the movement of the pedestrians. The transition rule defined for the movement of a pedestrian into an unoccupied cell is given by the so-called *transition probability function* (p_{ij}), which is defined as:

$$p_{ij} = N \exp(k_D D_{ij}) \exp(k_S S_{ij})(1 - n_{ij})\xi_{ij} \tag{3.19}$$

being k_S and k_D sensitivity parameters of the dynamic (D) and static (S) fields, with the normalisation N. The probability of transition (Equation 3.19) considers as well the existence of occupied cells (n_{ij}) by any obstacle (ξ_{ij}). A similar work is the one of Burstedde et al. [42] presenting similar results as in the works of Kirchner et al. [141, 142]. However, a limitation of this model is the need of calibration of the sensitivity parameters k_S and k_D for any new case study (e.g. building or studied crowd).

3.2.2 Biology Approach

Self-organisation in many biological systems has been typically studied by natural sciences [46, 55]. Swarms, trails and nest-construction are common examples of self-organisation in nature [22, 55, 143]. However, many applications beside biology has caught the interest of the scientific community in other fields of science, in special to path motion [200]. Biology-based models are sustained on the application of local *behavioural-rules*, which also affects the global behaviour of the system. Thus, a system (a crowd, for instance) is analysed based on the mesoscopic approach. In this section, fundamentals of self-organised systems (like swarms) and its further applications to the study of pedestrian motion are shown.

Mesoscopic Approach

Until now pedestrian dynamics has been understood and modelled based on macro- and microscopic definitions of a crowd. This means, a crowd has been defined as a homogeneous “entity”(with interactions similar to fluid dynamics) or as group of interacting “elements” respectively. The mesoscopic approach, in contrast, suggest an alternative scheme for understanding a crowd and its dynamics. In this sense, behavioural dynamics are described by considering the individual interactions among the pedestrians (as seen in the microscopic approach), but including their influence in the global behaviour of the crowd and in the other way around. Although the mesoscopic scope is a new alternative for describing pedestrian dynamics, it has been first suggested for the study of swarms and other self-organised biological systems [22, 46, 200]. However, its introduction allows further applications in other fields like path-finding in robotics [19, 20, 68, 211, 234] and modelling of crowd movements [71, 95, 96, 97, 150].

Swarm-based Dynamics. The study of self-organisation in biological systems is a relatively new area of scientific interest with increasing applications in many areas (like communications, robotics and transport) [22, 91]. In this sense, the research work about swarm behaviour achieved by Reynolds [200] is widely referred. The swarm behaviour is commonly associated to emigrant colonies of birds (looking for warmer zones during the change of year season) and bank of fishes (and their swimming manoeuvres for avoiding attacks of sharks or many other predators, as a way of defence). However, many other examples of self-organisation can be found in the nature (like ant-trails or nest-constructions) [55, 143].

In general, modelling swarm-behaviour is based on the description of the movement of a group of individuals (in the most simple case, defined as particle-like) with similar characteristics [200]. Self-formation is then yield by the fulfilment (by each individual in the swarm) of elementary behavioural rules. For instance, *leading-rules* (in migration-birds) or *allocation-rules* (i.e., choosing the inner-side of the swarm as the zone which provides more safety against predator-attacks) are some examples of behavioural rules for the modelling of swarm dynamics [122, 176, 200].

Understanding self-organisation in many biological systems has opened many other fields of research, an example of these is the so-called *ecological-robotics* [66]. Here it is assumed that behavioural responses (in biological systems) depends on the existence of information flow. This assumption is closely related to the ecological theory of Gibson [89], in which behavioural responses are assumed to keep dependencies on the available information of the surrounding. Thus, the new behavioural rules (in comparison to the original behavioural rules of a swarm) are of increasing complexity. An example is the model developed by Bicho and Schöner for path planning and its relation with a dynamic flow of information [19, 211]. In this model, behaviour is described by the heading direction and the walking speed of the robot. Both variables depend on the information flow in its surrounding. However, the final *"behaviour"* is the result of defined local behavioural rules. For instance, the change in walking direction or the reduction of walking speed for avoiding a possible collision. Similar works are those of Goldestein et al. [97] and Fajen [71], where pedestrian dynamics are also described by its walking direction ($\boldsymbol{\theta}$). This walking direction also may change when other pedestrians (or objects), the so-called *repellors*, are present in its vicinity. Moreover, it is assumed that each pedestrian has at least one location of interest (a so-called *attractor*). Then, the change in time of the walking direction of an observed pedestrian is described as:

$$\begin{aligned} \tfrac{d^2\boldsymbol{\theta}}{dt^2} &= -b\tfrac{d\boldsymbol{\theta}}{dt} - k_g\left(\boldsymbol{\theta} - \boldsymbol{\Psi}_g\right)\left[\exp\left(-C_1 d_g\right) + C_2\right] \\ &+ \textstyle\sum_{i=1}^{N} k_o\left(\boldsymbol{\theta} - \boldsymbol{\Psi}_{o_i}\right)\left[\exp\left(-C_3 \mid \boldsymbol{\theta} - \boldsymbol{\Psi}_{o_i} \mid\right)\right]\left[\exp\left(-C_4 d_{o_i}\right)\right] \end{aligned} \tag{3.20}$$

being C_1, C_2, C_3, C_4 empirical constants, k_g, k_o and d_g, d_o the goal (i.e, the point of interest) and obstacle contributing weights and distance to them respectively. The walking direction of the pedestrian is then $\boldsymbol{\theta}$. $\boldsymbol{\Psi}_g$ and $\boldsymbol{\Psi}_o$ are the angular direction to the goal and the obstacles respectively, and b is a so-called *damping term* which is suppose to *"smooth"* the change of pedestrian direction over the time. This model allows the description of the movement of a single pedestrian and the effect of further objects in its vicinity in simple scenarios (i.e., a room with one or several exits but no further walls inside the room) [70, 71]. However, some simulation runs with this model shows the existence of high sensitivity of the parameters of the model and the strong dependency existing between them, difficulting (in this way) any further modification to the actual values of the parameters in the model [45].

3.2.3 Psychology Approach

The psychology approach assumes that pedestrian behaviour is the result of several interactions given by socio-psychological processes. In contrast to the engineering approach, each member of a crowd is able to think and to behave according to the situation that the individual is experiencing [86, 87], and similar to the biological-approach, information is obtained from the surrounding environment of each individual. However, and contrary to the biological-approach, there is no flow of information, but a process of perception (commonly regarded to visual cognition). And by its means information is collected [88, 89, 175, 203, 205]. This leads to several visual-perception-based models [203, 205]. However, the existence of further behaviours (for instance, affiliative behaviour [217, 218]) are beyond the scope of these models. In this sense, an alternative model based on the social comparison theory (suggested in [134]) relates the natural tendency of individuals to compare themselves with other individuals in a similar situation). Although, Chapter 4 presents a detailed review of cognition processes and its relation with information-processing and behavioural responses, for clearness purposes, in the present section a short introduction to this topic is given.

Microscopic Approach

In general terms, human beings (since its birth) are suspected to the continuous stimulus of its surrounding environment (i.e., seen, heard, touched, smelled and tasted). Traditionally *psychological cognition* is related to the study of the mental processes involved in the perception and transmission of this information. In the microscopic approach of psychology-based models, behavioural responses are described based on two central points. First, the way by which information is obtained from the environment, and second on how this information is used for the elaboration of a response (e.g. looking for the shortest way to the exit). Until now psychology-based models consider the visual perception as the major way for collecting information [175, 203, 205]. Further models, in contrast, consider personal or group desires (assumed as a *"list of activities"*) as the unique source of information with which any behavioural response is elaborated [159, 207].

Visual Perception-based Models. Each pedestrian is modelled individually by assuming it as an independent entity with *thinking-properties*. The surrounding environment is visually perceived but with certain limitations of capacity, as suggested in [175]. An example is the model proposed by Sakuma et al. [205]. The model is based on the assumption that each pedestrian can collect a certain amount of visual information (that is, positions and walking speed of other pedestrians) and later use it for further *"decisions"*. Manoeuvres for collision avoidance among pedestrians are also possible, since the model assumes the existence of a so-called cautionary and critical region (also referred in psychology as personal space [105, 106]). Changes in walking direction are mainly based on the vicinity of other pedestrians to the cautionary and critical region (here assumed to be circular regions). When there is no possible collision, the pedestrian will maintain its direction of walking, otherwise it should "select" the optimal avoidance manoeuvre. In other words, a sharp decrease in its walking speed (called as urgent avoidance) will be taken when the future collision takes place inside the critical region, or a smooth decrease (called as smooth avoidance) when the future collision takes place in the cautionary region. However, this model presents high sensitivity in the selection of the storage time of information, the calculated time of any possible collision, and the radii of the cautionary and critical regions, leading to high number of urgent avoidance manoeuvres and "unnatural" jams among pedestrians.

An alternative model, is the suggested by Shao et al. [215]. In this model, perception is seen as a "list" of activities (or routines), whose fulfilment yields to basic reactive behaviours. Although pedestrian motion is based on perceived information of its surrounding, path maps are generated with a finite number of cells (similar to a CA-type). Thus possible new positions are limited by the size and shape of the cell as it occurs with CA implementations (as seen in Section 3.2.1).

Mesoscopic Approach

Again, crowd behaviour in built environments is assumed to be the result of one or more interactions of the type *individual-individual*, *individual-group of other individuals* and *individual-building*, which may occur (or not) simultaneously in a normal or emergency situation [223, 250]. Until now, behavioural responses have been studied based on these interactions. However the existence of further behaviours (for instance affiliative) are beyond the focus of the previous models. According to Sime, an affiliative behaviours take place in situations of high ambiguity [217, 218]. For affiliation is mean to the situation in which several members of the crowd (keeping a degree of familiarity or relation between them) adopt similar behavioural responses rather than individual ones in the assumption that this type of decisions increase their chances of success (or survival, in the case of emergency situations).

Model based on Social Comparison. The Social Comparison Theory (SCT) of Festinger [73], suggests the existence of a natural tendency of individuals to compare themselves with other individuals in a similar situation (as it occurs with affiliative behaviours). Le Bon named this phenomenon as *"collective mind"* [153]. In a collective mind individual responses tend (after a certain time) to be homogeneous, where *imitation* and so-called *contagion* behaviours predominate. Based on the SCT theory, Kaminka et al. [134] suggest that characteristic motion paths of pedestrians (in specific, line formations and bidirectional movement) are the result of several comparisons among pedestrians. However, the definition of a standard behaviour to be followed (similar to the behavioural rules in swarm dynamics) is not always obvious to other members of the crowd.

3.3 Capabilities and Limitations of the Available Models

The fulfilment of safety standards in the built environment has a central role in the criteria to be taken for the design or reconstruction of new or existing buildings, respectively. Unfortunately, the existence of crowd disasters during evacuations or collective events (Chapter 2, Section 2.1.1) show the need for the application of further tools and methodologies of risk management. However, due to the nature of these events, fatalities are commonly not well documented, yielding to a lack of knowledge in this field.

Models of crowds and pedestrian dynamics appeared as a tool which should enable the study of emergent behaviours of the evacuating crowd. However, the non-existence of clear defining criteria of a crowd and its upcoming interactions yield to a broad number of models (Figure 3.1). Section 3.2 reviews the criteria and main assumptions considered in each (until now) existing model for describing evacuation dynamics. Moreover, the study of a crowd and its dynamics varies in a way in which a crowd and its elements are defined (as previously seen). In this sense, pedestrian dynamics inside a crowd can be explained macro-, micro-, or mesoscopically.

In this study, the nature of pedestrian dynamics is understood as a self-formation phenomena, in which several interaction rules among each individual in the crowd are present. The type interaction rules chosen for describing pedestrian dynamics has a direct dependency on the level of detail in which the system (crowd) is described. In this sense, local, global or mixtures of both types of interaction rules are used in microscopic, macroscopic and mesoscopic descriptions respectively. Therefore, the capacity or limitation of a model for describing certain behavioural responses (i.e., motion paths) depends on the level of description and the nature of the interaction rules (engineering-, biology- and psychology-based).

An example of this, is the heterogeneous nature of a crowd. On a macroscopic level, a crowd is defined as a homogeneous “entity” whose behavioural dynamics average values. This type of descriptions are commonly used when high concentrations of people are present (like train-stations in Japan or China or Mecca-pilgrims) and the average dynamical behaviours are of special interest. However such models do not allow the study of internal-interactions taking place among the individuals in the crowd. Furthermore, homogenisation of pedestrian properties and behavioural response limits a deeper understanding of its dynamics. In opposition to this, the approach provides an improvement in the calculation of evacuation times based on the hydraulic-model (Section 2.1.2).

On the other hand, microscopic models allow the individual characterisation of each pedestrian (heterogeneity). Interaction rules are also defined individually and may vary from one individual to another. By this means, defining individual interaction rules allow a better understanding of the characteristic emergent-behaviours in real evacuations (Section 3.1.2) and better estimations of evacuation times. However, the validation of the defined interaction rules in real scenarios is not always possible and sometimes questionable (especially those based on Newtonian-like motion laws [209]). The mesoscopic approach allows the description of individual and global interactions. This enables the study of possible effects of local behaviours over global ones (and the other way around) and present a more promising approach in comparison to those considering separate local or global interactions.

3.4 Requirements for Future Models in Evacuation Dynamics

The present study is mainly focused on the development of a new model for describing evacuation dynamics. However, due to the nature of pedestrian phenomena, the new proposed model should provide a mathematical expression for describing pedestrian motion,in the context of an evacuation, based on visual perception. In this study, pedestrian dynamics are understood as a self-formation phenomena, where emergent formations are the result of interactions among the members of the crowd. These interactions are commonly referred as those given between individual-individual, individual-building and individual-group of persons [102, 197, 221]. Together with this, such interactions should be also influenced by the situation experienced by the other individuals [115, 224, 226].

With regards to safety in the built environment, the present study proposes the usage of pedestrian dynamic models as a way to obtain more detailed information regarding behavioural dynamics due to evacuation processes. Until now, safety in the built environment is only related to the application of construction norms and standards, by taking calculations of evacuation times as a reference (Section 2.1.2). However, the lack of knowledge regarding behavioural responses in evacuations makes difficult to obtain good estimations. Thus, simulation tools represent an alternative source of the missing data.

In addition to this, the introduction of a risk management methodology has been suggested as an alternative tool for the reduction of fatal events. For this study, the estimation of the vulnerability of the occupants inside buildings and their effect in evacuation times (as suggested in Section 2.2.1) is of special interest. Therefore, any new proposal of a model for the description of evacuation dynamics should be also flexible in a way that local and global interactions can be described (as given by the mesoscopic approach), but also the individual characterisation of each pedestrian should be possible (like in the microscopic approach).

Chapter 4
Psychological Aspects of Human Behaviour in Evacuation Dynamics

Defining which elements or processes are natural or implicit to human behaviour regarding evacuations is not trivial. For example, in classical psychology human behaviour can be assumed to be motivated by concrete stimulus or to be the result of several interacting characteristics and mental processes. The present study follows the Ecological Theory of Gibson in which human behaviour is assumed to be the result of interactions (the so-called perception) between the individual and the physical characteristics of the environment that surrounds him. In this sense, Section 4.1 gives an overview of the elements which may define human behaviour and the way in which the process of decision-making takes place. Moreover, complexity of individual behaviour resides on the fact that the perceived situations among several individuals may vary. A reason for this, is the fact that the characteristics and cognitive processes (conscious and unconscious) may not present the same scale for all the individuals. Regarding to evacuation dynamics, interactions among individuals are important. In special, when the evacuation involves big groups of participants (or crowds). In this sense, an overview regarding collective behaviour within evacuations and collective events is given in Section 4.2.

4.1 Individual Behaviour

Defining human nature is a complex task which requires the understanding of multiple fields of science. Evolutionary psychologists, for example, assume the existence of an *universal* human nature [136]. This assumption is strongly related to the *determinism* school, which considers that any event of the universe (including human behaviour) is completely defined by a finite number of events. In other words, human behaviour is causal and is determined by series of previous occurrences [127]. In this sense, two main conceptions of human nature have been taken. The first one considers the human nature as a *totality*, where all behaviours and psychological characteristics in the human being are present in all individuals. The second one, in contrast, considers that a total vision is too broad and hardly a concrete definition of human nature, and suggests the characterisation of human nature by means of several *subsets* of characteristics. In this sense, Buss [43] considered human nature to be a function of so-called *qualities* (mainly biology- or psychology-based [41]), which differentiate the human beings from other animals of the planet. In the present study we agree with the later one in which human nature should be defined by means of the *degree* of the human-qualities present in the individual (as suggested by Sober [229]) and not as a total and universal nature. Moreover, such degree of qualities may vary from individual to individual. And therefore, an "individual" nature of human behaviour comes out from such variation.

Study of Human Behaviour

Psychology (from Greek: *psyche*: soul, self or mind; and *logos*: speech) is the scientific field which traditionally studies the behaviour of individuals, their mental processes and the interaction between these processes [85]. According to classical psychology human behaviour is influenced by several factors. The most frequent are perception, cognition, emotion, personality, and interpersonal relationships. However, the exact connection between them is still under study. Lawson (for instance) suggests that any behavioural response is influenced (directly or indirectly) by several objective and subjective factors, as seen in Figure 4.1. In general terms, the performance (or influence) of an objective factor over the behavioural response are considered as measurable, since most of these factors are conscious or controlled processes. Thus, the objective factors are also referred as quantitative ones. In opposition to this, the subjective (or qualitative) factors do affect the behavioural response of an individual but the degree of their influence cannot be measured, since most of these factors are uncontrolled and unconscious. For example, the decay of attention (a controlled process) of an individual may be influenced by the tiredness (uncontrolled process) that the person is experiencing.

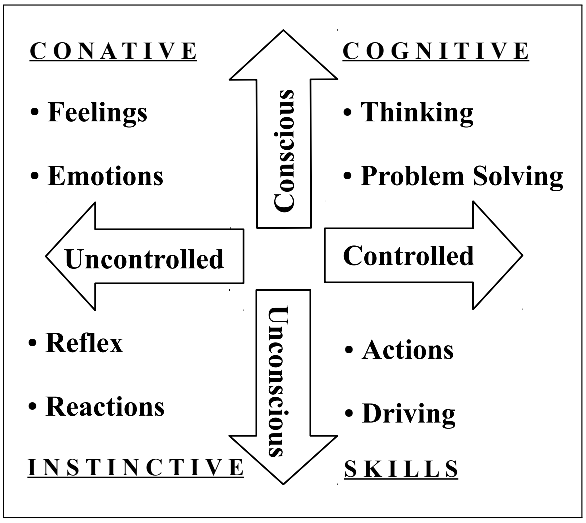

Figure 4.1: Human behaviour and its psychological processes, according to Lawson in [152].

However, an exact estimation of the degree of tiredness of the individual may result ambiguous, and in the case that it could be obtained, it may differ from individual to individual suspected under similar situations. As mentioned previously, the present study is focused on the development of a mathematical model describing evacuation dynamics of crowds. Moreover, the model shall also integrate psychological aspects of human behaviour regarding evacuations.

The inclusion of both influencing factors in a mathematical model may be desired but practically not possible, in special due to the difficulty of measure of subjective influencing factors of a behavioural response. Therefore, for simplicity, our proposed model only considers the objective part of a behavioural response and leave the subjective one to future works.

4.1.1 The Behavioural Response: Definition and Starting Element

A first step in the development of a model for evacuation dynamics is the definition of what a behavioural response should be and their influencing factors. The emergence of any behavioural response results from a particular motivation [60, 76, 201]. This motivation will then *energise* and *direct* all upcoming actions (i.e., behavioural responses) of the individual, which are required to the *fulfilment* of this motivation [60]. Motivation can then define the *starting stimulus* of the human behaviour. However, this motivation can be also of complex nature. Maslow (for instance) outlined the theory of motivation based on the satisfaction of several needs. This theory is called the *theory of self-actualisation*. This means that all individuals look for the use and actualisation of their personal potentials according to their relevance (or given hierarchy) [76, 165, 166].

The assumption that motivations are the starting point of behaviours has been well accepted by the scientific community. However, some other factors should be considered. In this sense, Kaufmann suggested that human behaviour is not only the result of internal stimuli (the so-called *needs*), but also of external ones (referred as *situations*) [136]. These considerations are supported by the environmental and cognitive psychology.

Environmental Psychology

Environmental psychology was started in the USA during the middle of the 50's - beginning of 60's as a special field which was followed by several scientist in Europe. However, it was until the beginning of the 70's when this field was recognised under this name [23]. Environmental psychology concerns the physical characteristics of the environment that influences human behaviour [193], the interaction between the individuals and their socio-physical environment [235, 236]. This interaction is commonly referred as *perception*. Several schools and theories have been developed in order to understand their influence on human behaviour. The most important are summarised.

The Psychology Behind Perception. In general, the psychology of perception studies the *correspondence* between psychological processes (due to perception) and the characteristics of the socio-physical environment. In this sense, several theories have been developed in order to understand the role of perception in human behaviour. Thus, the term perception has been defined under diverse perspectives. The most important approaches are shown in Table 4.1 and briefly described as follows.

School / Scientist	Definition of Perception	Developed Theories
New Look	An *"inside-outside problem"*	—
Gestalt	A *biological phenomenon*	Isomorphism
Bruswik	An *ecological validation process*	Lens Model, Probabilistic Theory
Gibson	The result of *ecological characteristics*	Ecological Theory

Table 4.1: The concept of perception and its schools.

- The New Look and The Gestalt. Under the perspective of the New Look, perception is defined as an *"inside-outside problem"* [6]. From the inside-outside concept, it is mean the interaction between the individual (*inside*) and its environment (*outside*), where perception the interphase between them. The *Gestalt*, in the other hand, considers the perception to be a *biological phenomenon*. This phenomenon is based on the *Theory of Isomorphism*, which assumes the existence of neurological innate mechanisms which are common to all the individuals [23].

- Ecological Theory of Gibson. On the other hand, Gibson considered perception as the result of *gathering* ecological information of the surrounding environment, where information is collected by the individual as sensorial input. Such input (in accordance to Gibson), is invariant and takes part in the so-called *stimulus flux* of the environment [87, 88]. Therefore, Gibson gives more importance to the perception due to visual stimuli and its related processes [86, 89] than to other forms of stimulus.

- Probabilistic Theory of Brunswik. In his works, Brunswik defines the perception as a *"ecological validation process"* between environmental cues and functional process of the individual [36]. *Validation* is referred to the comparison process of the collected environmental information for a posterior use. The environment, according to Brunswik, is understood as all the measurable characteristics present in the surrounding of the individual [37]. The validation process was later denoted as the *"Lens model"* [39].

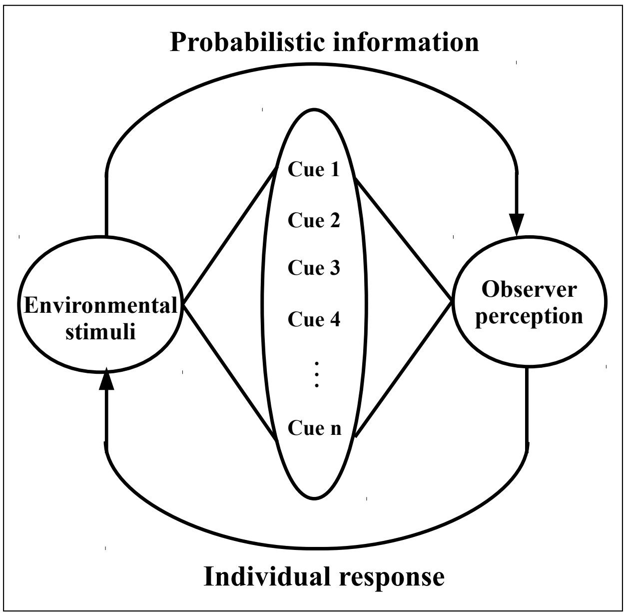

Figure 4.2: The Lens model of Brunswik [39].

In the lens model, the individual may not be in direct contact with a *stimuli source* of the environment. However, it is assumed that an interaction between the individual and the source takes place. This interaction is then given by means of cues sent from the environmental source and being received by the individual. Such interaction opens a so-called *"connecting bridge"* between these two elements, as seen in Figure 4.2. Moreover, Bruswik considered that such interaction is *"imperfect"*, and only *probabilistic* information of the sent cues are perceived by the individual [106].

Therefore, validation of this information is important and it turns into iterative when several cues are involved.

The Psychology of Social Interactions. In general terms, the process of perception shows the way in which the individual interact with its surrounding environment. However, beside this individual-individual or individual-environment interaction, further interactions should be considered. For instance the interaction of the observed individual with other individuals or group of individuals. For this purpose, several theories regarding the way in which such relationships take place and their influence in the perception process have been developed. Thus, the most relevant theories in this field are shown as follows.

- The Field Theory of Lewin. Lewin (the *"founder of social psychology"*), considered that any individual has a so-called *life-field* surrounded by the environment. Here is important to emphasise that the term environment corresponds not only to the stimulus that the surrounding may transmit, but also to the presence of other individuals in the vicinity of the observed individual. The limit where both fields (the individual and the environment) meet together is called *confined zone* where physical stimulus and execution of actions take place [23, 158]. Lewin studied such interactions and assumed that behaviour is the result of situations occurred in the confined zone [156, 157]. This assumption keeps close relation to the ecological theory of Gibson, by assuming that any behaviour (B) is a function of the influence of the environment (E) over the observed individual (I). This means,

$$B = f(I, E) \tag{4.1}$$

where Equation 4.1 was called the *psychological equation of behaviour*. However, this expression just represent the abstract concept of behaviour and do not provide deeper information about how the interactions environment-individual may take place.

- The Social Approach of Bronfenbrenner. Bronfenbrenner, in contrast, developed the so-called *Ecological System Theory*. In this theory the environment is subdivided into micro-, meso-, exo-, and macrosystems [31, 32] (as seen in Figure 4.3). In all theses subsystems, the individual may be or not present directly, however interactions among all levels do exist. For instance, the microsystem consideres the observed individual (as the minimum level of description) and his immediate "environments" (i.e., family, beliefs) with whom the individual interacts.

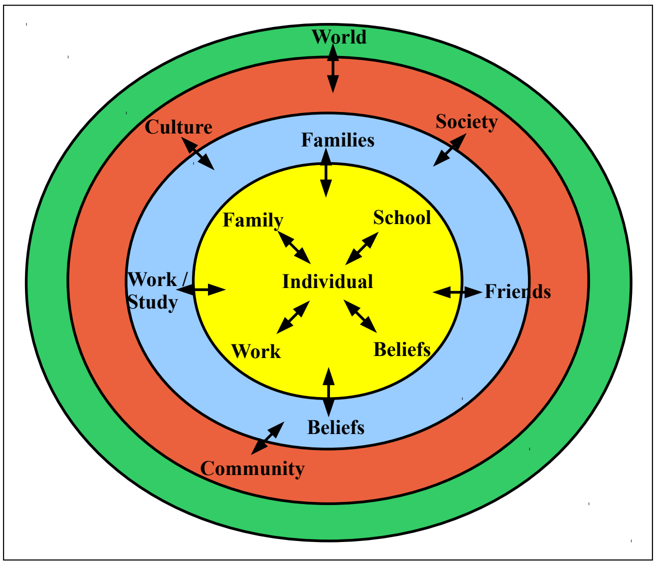

Figure 4.3: The ecological system and its classification: microsystem (yellow circle), mesosystem (blue circle), exosystem (red circle), and macrosystem (green circle).

The second level of interactions are given in the mesosystem. Here immediate environments interact with other. As a result several influences among environments may take place. For ins-tance, the personal belief of the individual (a microsystem environment) may be influenced by other individuals. The third level is the exosystem, where all external (and independent) environments are located (e.g. community, culture).

The exosystem refers to all the external influences that subsystems of lower levels may experience. In this external level, the individual may or may not interact directly but it may be influenced (e.g. cultural influence). Finally, the macrosystem is the largest system (and thus the most general level of description) which contains all other minor subsystems.

4.1.2 Decision-making Process: Available Models

As explained before, a behavioural response is influenced by objective (cognition or abilities) and subjective (feelings or reflexes) processes. This study focuses on objective processes which may influence the behavioural response. In particular, to cognition and the relation to the decision-making process in the context of evacuation dynamics.

Cognitive Psychology

In general, *cognitive psychology* studies the mental (conscious and unconscious) processes involved in a behavioural response. Moreover, the *environmental cognition* focusses on the translation of external situations (or *"physical reality"*) into internal processes (or *"mental states"*) like attention, perception, memory and thought [135]. In accordance to cognitive psychologists, these mental states may directly influence the behavioural response of an individual [163]. However, the way in which these mental processes are interconnected is under study. In the other hand, computational science has been focused on the study of the human mind and its functioning. Introducing, for this purpose, the *information processing theory* [199, 254]. In general terms, and similar to a computer, the human brain needs three elements for the elaboration of a behavioural response: the *incoming data* of the exterior (or environment), a *memory unit* for the storage of selected information, and a so-called *elaboration middle-process* under which the information will be processed and converted into a behavioural response [69, 254]. However, a detailed information processing may then consist of further intermediate steps as seen in Figure 4.4.

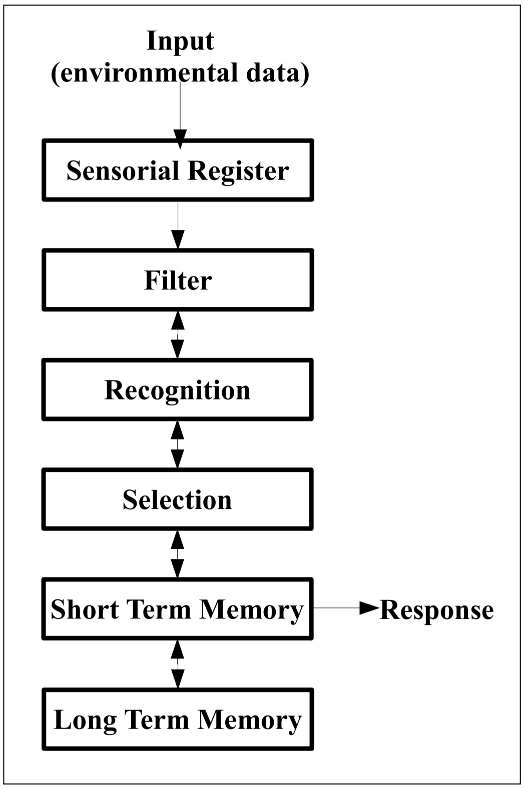

Figure 4.4: A common model for information processing. Example schema of a information processing unit. Taken from [199].

Nevertheless, a generalised information processing can be summarised in its three main parts. The first one is the *pre-processing*. Here, incoming data (or environmental stimuli) are registered (or perceived), filtered and recognised in accordance to several para-meters. In a second step the selected information will be briefly stored in the so-called *short term memory*. In this step it is possible to formulate a behavioural response according to the stimuli received. However, in the case that this information (or a part of it) is not used in the immediate time, it would be stored (the third step) for its possible use in the future. This long-term storage unit is typically known as the *long term memory*.

The Process of Attention. Since its birth, human beings receive constant stimulation from the surrounding environment. This represents an important quantity of information which, in theory, human beings are suppose to collect and to process along its life. However, this do not occur since the capacity of perception and processing information in human beings is a limited resource [163, 175, 181, 254]. For instance, in the case of the process of attention, the human do select a part of the *stimuli information* from the environment. The rest of information is then *"ignored"* or do not take part (at least in a direct way) in the final response. This process of selection is called *selective attention*. However, a clear definition of the functioning of this process is not known. Thus, several models definitions for the selective attention and information processing may exist.

For instance, Broadbent compared the process of selective attention with a type of serial *"sensorial filter"* [29, 30]. This is, when two messages are given instantaneously, only one of them is processed at time, meanwhile the second one remains on the filter and *"waits"* its turn to be processed. In other words, the sensorial filter selects information based on the attributes of the stimuli like volume or strength of the voice. However, other attributes like previous experience on the stimuli [251], the nature (i.e., visual or touch stimulus) [5] and meaning of the stimuli [98], together with its conscious and unconscious processing [255], are not taken into account [178]. Moreover, Deutsch and Deutsch suggested the influence of ownership and relevance of the message in selective attention [62] and their effect on behavioural responses.

On the other hand, Treisman considered the selective attention as an *attenuation* or hierarchical processing (in special to auditive stimulus) [243, 244, 245, 246, 247]. Although the suggested steps for information processing are more elaborated than those suggested by Broadbent, this model may suppose an unlimited perceptual capacity (at least for the pre-processing step) by considering the collection of all messages. Once the complete information is collected, a level of threshold is assigned to each message. Those messages with higher threshold influences the behavioural response directly, meanwhile the influence of the messages with lower threshold is *attenuated*.

A more extensive model for human information processing is the suggested by Kahneman [133] (Figure 4.5). In this model, the level of attention is affected by external and internal factors as well as by personal interests and dispositions [94]. Treisman et al. [247] considered the existence of *"pre-processing"* steps like *pre-attention* and *focused attention*, which make a pre-selection of the incoming information. Concentrating in this way the available resources in the object or situation of interest. These processes suppose to be less expensive (in terms of information processing), than those where the whole information is analysed without any previous selection. In this sense, Kahneman suggested the existence of a *central elaboration unit*, which coordinates and distributes the available resources [133].

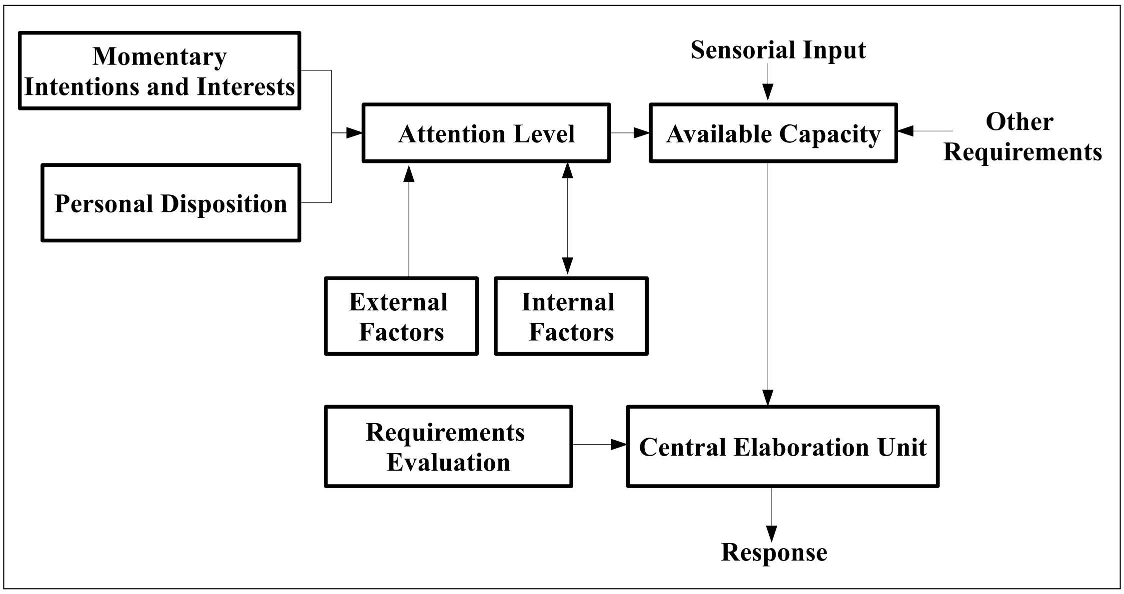

Figure 4.5: The model of attention capacity of Kahneman. Taken from [163].

Similar to computational information processing, the central unit also elaborates and evaluates the possible responses due to a certain stimuli or environmental situation [254], by considering the *available capacity* in the distribution of resources. Therefore, attention is to be first prioritised in levels (the so-called *attention level*) and resources are assigned to those *events* with higher levels of attention (Figure 4.5). Once the available resources are assigned, information is sent to the central elaboration unit in order to be processed and a final response is obtained.

Beside the definition of attention as a step in the processing of information, attention is also defined in terms of vigilance level of the individual [164]. However, vigilance level depends on the degree of physical and psychological brain *activation*[3]. Thus, vigilance is not constant and tends to decrease after certain time. Moreover, this biological activity can be influenced internally (due to the personality of the individual or to the existence of previous experiences) and externally (the so-called environmental stimulation) [268].

The Perception Process. Together with cognition, further processes are directly involved in the resolution of a response due to a certain environmental

[3]The term activation is related to the level of activity of the human brain (*biological activation*). This activity can be measured in laboratory by an electroencephalogram. Stroh [237] studied this biological activity and established the lower ($8-21$ cycles per second in the alpha rhythm) and the higher level ($12-30$ cycles per second) of activity of the human brain.

stimuli. Examples of these are the collection and interpretation of environmental data [163]. The process of data collection is commonly referred as *sensation*. In this sense, data is collected by means of the *natural receptors* of the individual. Such receptors are so-called *senses* (like seeing, hearing, touching, smelling and tasting). The collected sensorial data is transmitted to other sections of the brain and interpreted. The complete process is denoted as *human perception* [202]. Here the brain acts as the central unit [133] which selects, organises and transforms these data into information. However, the process of perception has been understood in different forms, and thus several models explaining its function exist.

The Gestalt school, for instance, suggests that perception works in an organised way [147]. The principle of this assumption is the *theory of conciseness or prägnanz*, which assumes that the sensory data is organised by determined rules of regularity, order, symmetry and simplicity. From this idea further theories have been developed in order to obtain a deeper understanding on the manner in which the collected data is organised and analysed. Therefore the laws of closure, similarity, proximity, symmetry, continuity and common fate are frequently referred.

On the other hand, Gregory [101] gives more emphasis to the use of previous experience in the process of perception. According to him, perception is an *active process* of validation, where a *perceptive hypothesis* is formulated with the new received sensorial data. The hypothesis is then taken as valid if this new information corresponds with previous experiences. In the contrary case, the hypothesis is neglected or reformulated.

Gibson, in contrast, assumes perception as a *direct process* between the stimulus source and the sensors which collect the sensorial data [87, 88]. This assumption is directly derived from the *Ecological Theory*. Thus, the individual is able to obtain updated information (typically visual) of the surrounding environment and to elaborate the appropriate response due to the situation [86, 89].

In a similar way, Brunswik assumes the existence of a narrow relation between the perception of the environment and the response (actions) of the individual due to its surrounding [38]. This relation is the central point of the system and is individually defined. According to this, individuals have input and output channels. The type of the input and output (according to the model) varies in function of the *proximity* of the individual. For instance, a *distant* input corresponds to the psychological state of the individual (i.e., experience, motivation, emotional state and personality). Meanwhile, a *near* input is defined from the environmental context (i.e., physical objects and immediate sensorial stimulation) [163]. This input information is *perceived* by the individual and translated into output responses. The immediate response are the actions which the individual carries out. Then, these actions may later interfere on the future events as a distant output.

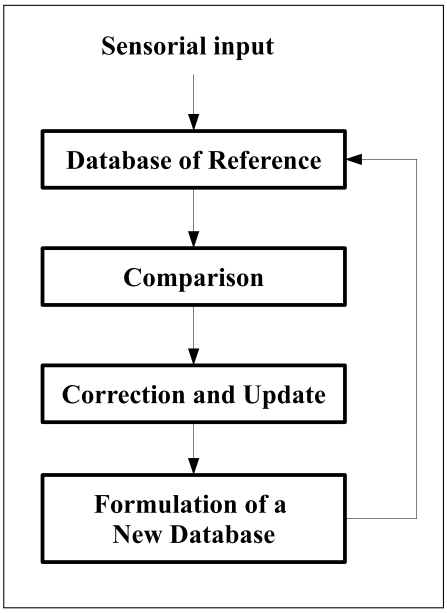

Figure 4.6: The cyclic procedure of the human perception suggested by Neisser [181].

In opposition to Gibson's assumptions, Neisser considers the perception as a cyclic procedure which is based on previous experiences and expectations [181] as seen in Figure 4.6. The starting point of the cyclic process is the *"database of reference"* of the individual which is formed on previous concepts, experiences and expectations. When new collected environmental information comes to the individual, this is immediately compared with the existing one. In the case of existing differences between them, the new information is used for possible corrections or updating the old database.

Once the old database is corrected, a new database is then formulated and stored as previous experience. Finally this previous experience is ready to use for the next comparison with the new future information and to start again the perception cycle.

The Process of Memory. *Memory* is the process by which selected information is stored. And is a field of interest in cognitive psychology which has been studied in the last decades [10, 13]. However, not everything regarding to memory is known. The model suggested by Broadbent, for instance, assented the basis of human information-processing and is frequently taken as a reference [262]. The human memory is commonly classified into *sensory or working memory* and the *short and long term memory* according to the *retention time* [13, 163]. This classification is similar to the one suggested by the so-called *modal model* [10]. A brief overview to each type of memory is given as follows.

- The Sensory or Working Memory. This type of memory posses the briefest time of storage (around from 200 to 500 milliseconds after the item is perceived) [56, 180], therefore it is normally referred as the working memory. This memory is considered as a very active system and stores the information that is being using actively (or *instantly*). The information stored here is consider to be the one with which the individual thinks. This information has two sources: the new sensorial information, and the old information taken from the long-term memory [163]. An example of this memory is when an individual wants to drive bicycle after several years of non-use. The individual may use the information stored in the long term memory in order to *remember* how is the functioning of the bicycle. But also some instantaneous information (like position and speed) is needed to maintain the equilibrium by riding the bicycle. According Baddeley et al. [12, 13, 14], the working memory has a *central-execute unit* which receives new sensorial input and classifies it according to its nature (acoustic, visuo-spatial or verbal). This information is briefly stored and *re-called* by the central executive unit once the information is needed by the individual.

- The Short Term Memory. A part of the information contained in the working memory will be stored in the *short term memory* (STM)[4]. However, this retention rate tend to decay after certain time (approximately 18 seconds) without information-rehearsal [188]. Thus, the STM optimise the storage process by recoding sensorial information. Here the visual input is translated into verbal and acoustic information, as suggested by Conrad [52]. Similar experimental results were obtained by den Heyer and Barret [61], which reinforces the idea that the short term memory works verbally. In spite of this optimisation, the STM do have limitation in capacity (the so-called *"five elements plus-minus two elements"*) according to Miller and his experiments [175].

- The Long Term Memory. The long term memory (LTM) is the last step in the modal model. While in the previous steps (the working and short term memory) the duration and information capacity are better described, this do not occur in the LTM [13].

After several studies it has been found the existence of a codification procedure similar to that in the STM but its functioning is still not well clarified. Tulving [248, 249] suggested that the LTM is divided in two processes: the *declarative*, which is subdivided in episodic and semantic, and the *procedural* memory. The declarative memory refers to all the information which can be used consciously (specific events or procedures). The episodic memory (as it

[4]This storage-unit contains the information for a period of time not longer than 30 seconds, with an optimal retention time of 6 to 12 seconds [163, 188].

name says) is referred to specific events occurred in a specific order in time. These past events are mainly personal experiences and sensations present as a consequence of those experiences. In the other hand, the semantic memory is mainly referred to the specific concepts, their comprehension and posterior knowledge obtained form them. The procedural memory considers procedures of use or movements (e.g. the procedure needed to ride a bicycle and the movements of the body which this implies). However, other classifications of the LTM can be found and are open to discussion [25, 26]. Then, the most accepted division of the LTM is the proposed by Squire [231], who divides it into *declarative* and *non-declarative*. The declarative (or explicit) memory is referred to the storage of past facts and events. Into this classification the episodic and semantic memory are also included. The non-declarative (or implicit) memory is based on four subdivisions which considers skills and habits, priming or preparation processes, simple conditioning and non-associative learning of the individual.

Even though the LTM stores big quantities of past information, certain losses are present. In this sense McGeoch and Macdonald [168] studied the effect named *interference*. The interference effect is given due to two main reasons. First the similarity in nature of already stored information (past information) with the process of memorising new incoming information (the so-called *retroactive interference*) which may create confusions or losses in precision of the new information to be stored (for example, trying to memorise the new time schedule of the bus which we frequently use). And second the *proactive interference* which works in the inverse. This is, when the new information interferes with the previously stored (like trying to remember the old time schedule of the bus which we frequently use and now its time schedule has suffer some changes).

The Process of Thought. Thought is another cognitive process which also takes part in human behaviour. The process of thought consists in the manipulation of the incoming or available information (sensorial or recovered from memory). This manipulation may have or not a precise objective [169]. Thought without a precise objective is considered to be *unconscious*. However, when a particular objective exists this is considered to be logic and therefore *conscious*. Freud made also considerations in the same direction and divided the human mind in three different levels of consciousness: *pre-conscious*, *conscious* and *unconscious* thought [78]. Piaget realised several studies concerning the growth of thought in children and suggested that human intelligence is conformed by several *"systems"* which change along its life. The contact of the individual with its environment is also another factor which modifies the original systems. For Piaget human behaviour consists of three main systems: *organic* (referred to those hereditary characteristics and instincts), *sensory-motor* (to those learnt from past perceptions and their corresponding responses) and *symbolic or thought* systems [189]. According to Piaget when the individual is born all these systems are in equilibrium, but each new incoming information of the environment may break this and will start to look for a new equilibrium point. This process is called *assimilation* [163].

4.1.3 Implications to this Study

The present study is focused on the development of a mathematical model describing the dynamics of a crowd within an evacuation. Moreover, the model shall also integrate psychological aspects of human behaviour in this context. A behavioural response is influenced by subjective and objective factors proper to the human nature. Then for simplicity, our proposed model only considers the objective part of a behavioural response and the corresponding response-elaboration processes. Examples of these objective factors are the cognitive processes of perception, attention, uses of memory and thought. In this sense, a behavioural response is the result of a processing of sensorial information of the environment. In this study, the behavioural response of a individual within an evacuation is described in terms of its position and walking direction (as presented in Chapter 5). Moreover, when the environment that surrounds the individual changes, new sensorial data emerge. Thus, the behavioural response of the individual will be then modified to this new situation, similarly to the individual-environment interaction proposed in the Ecological Theory of Gibson (in page 55). However, not all the available environmental data can be perceived and processed by the human being, but a part of it. This implies a pre-processing step, as suggested by Kahneman (see page 60). Perception in our simulated individual is assumed to be a direct process between the stimulus source and the sensors of the individual (Ecological Theory). However, previous experiences and personal expectations, as suggested by Neisser (page 62), are not considered in this research and remain left for future works. Therefore, only the sensorial data which has been ”perceived“ by the simulated individual will be processed and considered for the elaboration of a new behavioural response, in a similar way as the working memory.

4.2 Collective Behaviour

Until now the study of human behaviour has been defined as the response due to diverse interactions of the individual with its environment: *individual-individual, individual-other individuals or individual-inanimate objects*. In this section, the environment and the interactions that may appear are studied in more detail. In general, the *collective behaviour* is assumed to be the result of one or more interactions occurring or not simultaneously in a determined event [223, 250]. Collective behaviour is typically defined as a spontaneous and non-structured response of a group of individuals in unexpected and frequently dangerous situations [224]. When the danger has decreased or has been *assimilated* by the individual, the collective behaviour may change into a more structured response [226]. Together with this, it has been found that individuals tends to form groups according to several intentions. Loftland [161] classified them into crowds and masses. However, both terms are commonly misunderstood. For instance, a *crowd* is a group formed by relative big number of individuals which are reunited without any apparent common objective, while the *mass* do have and its behaviour is directed into its pursuit. Further classifications like the one of Smelser [224], suggest the division of collective behaviour according to the people's response to a certain situation. Therefore collective *outbursts* (like panics, crazes, hostile outbursts) and collective *movements* (or social movements) may also be referred. When factors like size, frequency of congregation, frequency of polarisation and the degree of psychological permanence in its members are considered, these groups can be classified into *mobs* and *audiences* [33].

4.2.1 Elements of Collective Behaviour

As already mentioned, collective behaviour is the result of one or more simultaneous interactions between the members. However, the way how these interactions take place depend on the *characteristics of the members* (not only physical but also the role taken that each member) and on the manner that *information is diffused* among them. A generalised belief regarding on scaled emergency situations is the tendency to the panic in the presence of chaotic and unpredictable behaviours among the individuals [153]. This belief is commonly linked to the diverse nature of the members of the crowd and how the emergency shows up. Turner and Killian [250], for instance, studied several events where collectivities were involved and they noticed that (independently of the nature of the members or the emergency) six elements are observable.

These elements are *uncertainty* regarding the new situation, *sense of urgency*, *communication of the perceived situation* (like mood and imagery), *constrain, selective and individual suggestibility* as well as *permissiveness* (for example, to allow others to take the leadership in the situation and actions to be taken by the whole members of the crowd). Thus when all these elements are present in the crowd, then this is defined as an *"elemental crowd"*.

Then, information and its diffusion plays a decisive role during an emergency occurrence. But as it is known, information may not be transmitted at the same time to all crowd members involved. Here *formal* and *informal channels of communication* are frequently present [250]. In this sense, formal channels are normally constituted by authorities or those defined previous to the emergency. Meanwhile informal channels are spontaneous ones which are formed once formal conducts of communication during the emergency have been broken (due to a mechanical failure, for instance) or are not longer valid (like by the change of the group leader or by the appearance of new behavioural norms or procedures to be followed). Moreover, this informal way of communication plays a central role for the development of rumours. A *rumour*, according to Turner et al. [250], is the characteristic mode of communication in collective behaviour, by which norms and actions emerges. However, due to the informal way which it emerges, rumours are commonly assumed as negative and with lack of objectivity about the situation which is being experienced by the group. Nevertheless, rumours may also control the actions to be taken by the members of the crowd, like the development of the collective mind proposed by LeBon [153], or the generalised belief suggested by Smelser [225].

4.2.2 Classification of Crowds

One important differentiating factor among crowds is the way the members are coordinated. Here behaviours of *solidarity* or *individuality* among the crowd are commonly present and therefore, different strategies to confront the situation will be taken by the members [250].

For instance, the solidary crowd is based on the predominant belief of solidarity between their members. Thus, the available resources and actions are focused to the accomplishment of the common objective and cooperation. An example of this, are the groups of rescue, and spontaneous *"helpers"* which focuses their resources on helping those individuals (like aged- and handicap-people) which are not able to leave the scenario of danger by its own.

In the other hand, the *individual crowd* each member focuses its available resources and actions into their individual objectives. Here, competitive and less cooperative behaviour are present. Examples of this are the riots and mobs, where the involved members mobilise in order to be into the first ones in pursuing the objective (like the exit door). Behaviours like this which may scale into violence or panic, and are common when an scaled emergency situation occurs and the members of the crowd do not obtain enough information about the situation [250] .

4.2.3 Emergent Self-Organisation

As explained in Section 3.1.2, self-formation is a process in which global motion patterns emerge due to local interactions among members of a crowd. Typical examples are self-organised biological systems like swarms, bacteria, insects and mammals [22, 46]. However, self-organising behaviour is also present in humans, particularly in pedestrian crowds [9, 34, 51, 109, 111, 113, 119, 128, 153, 174, 177, 198, 224, 250]. Moreover, this behavioural patterns may also change according to the situation (for example, due to the absence or presence of an emergency or personal uncertainty) [55, 58, 114, 115, 209, 212]. Further examples of emergent self-formations in normal and scaled emergency situations are given in chapter 3, section 3.1.2.

Emergency-scaled Situations: The Way Into Panic

Panic may be present when people are in dangerous situations and the means of leaving such situation are limited [226, 250]. Panic is also considered to be the most frequent case of scaled fear. But even though panic is frequently related to situations where competitiveness among the crowd members is present, not all situations of this nature may conduct into a panic. Also *physiological* (like fatigue or toxicity), *psychological* (like experience of uncertainty, anxiety or isolation) and *sociological factors* (lack of information, failure in the communication channels, type and evolution of emergency) play an important role regarding panic appearance. Smelser [224], suggested the existence of an event-based process where the presence of the certain factors without an interruption may escalate into panic. Thus, panic will occur only when *structural conduciveness, strain, anxiety, precipitating factors, hysteria and mobilisation* are present at the same time. The general idea of the conduction to panic is here represented with an *electric-like RC-circuit* (seen in Figure 4.7). The suggested system consists of six subsystems, corresponding to the six phases (or events) for panic. All the subsystems are interconnected and only when the connection between them is closed (all switches are in the *on-position*) panic will appear.

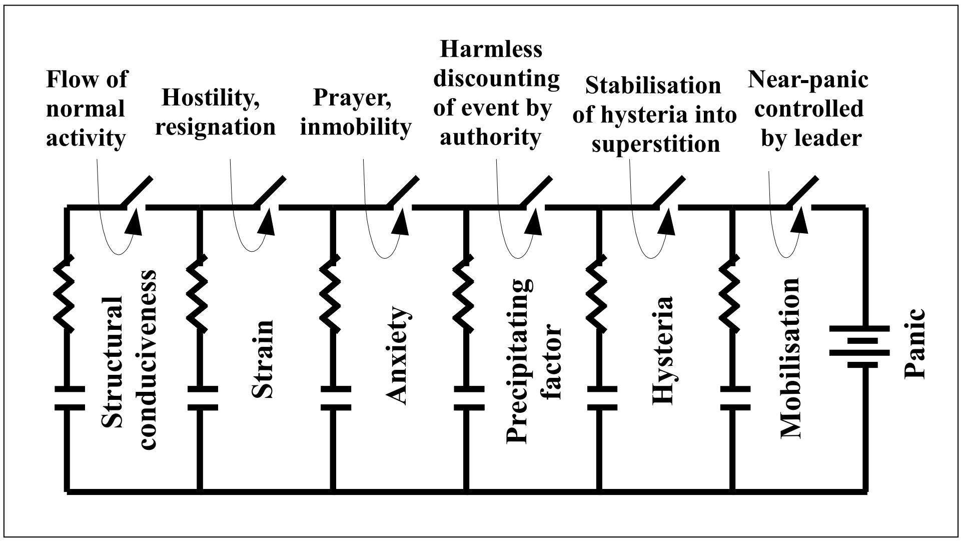

Figure 4.7: The process of panic appearence in the crowd when an escalation in the emergency occurs, suggested by Smelser [224]. Here, this process is represented with an electric-like RC-circuit.

Each subsystem consists of three elements: a electric-switch, a electric-resistance (R) and a electric-condenser (C). The electric-switch in the on-position provides continuity in the subsystem. In electrical theory, when the system is in the on-position, the condenser (C) starts charging and tension will exponentially increase until a maximum value. If the switch goes into the off-position, the tension will decrease exponentially until a value of zero. This analogy to the appearance of panic results important, in order to understand its evolution and functioning.

The *structural conduciveness* is referred to all factors that may conduce into a state of alarm or danger when an emergency occurs (like building conditions, communication-system, possibility of fire propagation and extinction). If conduciveness of a dangerous situation is minimised, even when an emergency situation occurs (for instance, controlling a fire inside a building without injuries), the connection to further phases is broken and a flow of normal activity will proceed. This is equivalent to the off-position of the switch in the first subsystem. In the case that the emergency situation is not controlled in the fist phase, *strain* among the involved people will appear. In the RC-circuit means that connection between the first and second subsystem is not broken and tension (or electricity) will *"pass"* to the second subsystem. People may start to perceive the danger as immediate instead of a distant event. Psychologically, this will raise the feeling of alarm and helplessness if the situation is not controlled in the immediate future. This increase of feelings and the diversity among them are in direct function of the susceptibility to danger, anxiety or rumours of the involved people, but also due to the lack of knowledge of the real situation. Therefore cultural and individual differences of response may be expected [224, 265]. If the strain situations are controlled hostility or resignation may appear among the individuals but no panic.

When the emergency situation is still uncontrolled (the switch continues in the on-position and no external event breaks the continuity of the conducting line between the first two subsystems) *anxiety* – a generalised belief– is the next phase to follow, and persons may start to present *psychological-tension* to the situation. In this step *fear* (a future-oriented emotion) is also to appear. Fear will arise due to the negative perception of the immediate future [265]. Sometimes fear is confused into *anger* which is a past oriented emotion. Anger appears due to a past negative event. According to Winstok [265], both feelings are not mutually exclusive, but behavioural resolutions differ. Anger tends to promote fight and violence meanwhile fear promotes to leave the danger and to flight [16]. A low control of anxiety among the involved individuals, may result in a *precipitating factor*. This phase can be seen as the *reinterpretation-phase*, where a new interpretation of the real situation is done. New values and norms may emerge here in accordance to the new generalised belief. Also new actions to be taken will be defined. This step may be decisive in emergency control, since a good management of the situation (moving the switch into the off-position) will result into harmless events. In the opposite situation *hysteria* will appear. Hysteria is given mainly due to the lack of information, which provides a generalised belief of ambiguity and tends to threaten or destroy [224]. If hysteria increases, the last condition prior to panic to appear is the *mobilisation*. During mobilisation two behaviours can be observed: flight and contagious or imitative reactions. And in accordance to Smelser, the combination of these behaviours produces a *maximum* in the response. This means that people will tend to increase their walking speed into a maximum possible (flight behaviour), in order to increase their chances of leaving the danger. This flight behaviour may be the result of an individual behaviour or the repetition (imitation) of the behaviour of the others [224].

Human Attitudes in Evacuation Scenarios

Beside panic and the related events to its occurrence, people may experience other type of psychological states, in special when the perception of danger increases. Such states can be identified as *attitudes*. Positive or negative attitudes may also orient the final behaviour of the individual and therefore of the crowd [138]. For instance, positive attitudes (like self-confidence and optimism) together with a solidarity-orientation of the actions to take, increases the percentage of a successful evacuation. However, this percentage of success also depends on the size of the group. In this sense, it may be expected that bigger crowds present a lower percentage of success than in smaller ones. However, little work in this field has been done in special with regards to evacuation dynamics. This situation opens new fields of research, specially due to the possible effect of the configuration of the building in the change of attitudes experienced by the evacuating crowd.

Anger-related Behaviours

Finally, a common topic related to *"uncontrolled"* crowds, is the presence of anger-related behaviours. It is commonly believe that once panic appears, scaled aggression among the involved individuals will appear. This is partially true, since anger not only results in physical or verbal aggression but also incentives the willing of flight or to communicate (non-aggressive behaviours) [50]. The escalation from non-aggressive to an aggressive behaviour will dominate when the anger among the involved members becomes more intense [50]. Winstok [265], found that aggression differs depending on the gender of the individuals. This means that women will tend to express their anger (emotion-driven), while men will tend to instrument their anger (goal-driven). Furthermore, highly-anxious individuals subjected to limited information will affect its affective modulation (i.e., defensiveness and negative affection) [241]. These findings show the importance of understanding the dependency between psychological state of the individuals experiencing a dangerous situation and their resulting behaviour and interaction with other individuals.

4.2.4 Implications to this Study

Collective behaviour is the result of one or more interactions of the type *individual-individual*, *individual-group of other individuals* and *individual-building*. Moreover, such interactions may occur or not simultaneously in a determined event. In the individual level of description (microscopically), each individual interacts with its surrounding environment (i.e., another individual, a group of individuals or inanimate objects). Thus, a behavioural response emerges from these interactions. In this section it was assented that collective behaviour is a type of self-organisation, in which any global motion path is the result of local interactions. And therefore, a mesoscopic description of its behavioural dynamics, in particular to evacuations, results more promising than the classical micro- and macroscopic descriptions (as discussed in Chapter 3, Sections 3.2.2 and 3.4).

The study of pedestrian dynamics is an emerging field of research. Thus, an homogenised use of terms and vocabulary in this field is still in process. In this sense, the review of a classification of crowds and their elements, as shown in this section, is relevant to this work for the reduction of vocabulary misuses.

Characteristic emergent self-organisation patterns in crowd dynamics were previously reviewed in Section 3.1.2. And avoiding redundant content, this section focused on scaled emergency situations, in particular to so-called panic. The different inducing factors of panic and their link to several attitudes and behaviours promotes its incorrect understanding. Therefore, the event-based process of panic appearance in crowd dynamics proposed by Smelser [224] results useful. In this section the process of panic appearance was explained by considering the similitude to an electric-like RC-circuit.

The present work is focused in the modelling of pedestrian crowds within the context of evacuations. Thus, a detailed understanding of individual and collective behaviour from the psychological point of view is relevant for this study. Our new mathematical model looks for a mesoscopic description of the self-formations in crowds including behavioural (psychological) factors. Until now, self-formations characteristic to pedestrian dynamics have been classified into normal and scaled emergency situations. The main aim in the present work is the development of a mathematical model able to simulate the characteristic patterns in evacuations in normal situations (here considered as controlled evacuations). Moreover, its extension to scaled emergencies and in particular to panic scenarios should be also possible but it is left for future works.

Chapter 5
Behavioural Model: PerPedES

This chapter presents the proposed behavioural model of PerPedES *(Perceiving Pedestrian Evacuation Simulator), a new approach for describing collective behaviour in evacuations. In this study, the behavioural response of each individual during an evacuation is modelled in terms of its position* $(\boldsymbol{x}) = (x, y)$ *and walking direction* (θ)*. As an introduction to this scheme, Section 5.1.1 presents the implications to modelling of evacuation dynamics especially due to normal situations. The used mathematical formulation for pedestrian motion is shown in Section 5.1.2. A central part of the model is the introduction of visual perception, which permits the adaptation of the behavioural response of an individual to the perceived situation. In this sense, an Object-Oriented model for individual visual perception is developed and presented in Section 5.1.6. In addition to this, the used time integration scheme for the numerical approximation of the evolution of the system is shown in Section 5.1.5. Due to the lack of information and standardised criteria regarding behavioural responses of individuals and their upcoming interactions in crowds in real evacuations, the validation of models by means of experimental data may be done but with certain limitations. In this sense, a tentative validation of our model based on the observed emerging motion patterns proper to evacuation dynamics is done in Section 5.2. Capabilities and limitations of the behavioural model are discussed in Section 5.3.*

5.1 Mathematical Formulation

In general terms, evacuation dynamics is a self-organisation phenomena which implies interactions at the inside of a crowd. Self-formation of motion patterns inherent to pedestrian dynamics result from these interactions. Moreover, the characteristics of these patterns vary in accordance to the situation in which the evacuation takes place. In particular, in normal or scaled-emergency situations. Initial formulations of evacuation dynamics were based on similarities between these motion patterns to some known dynamics. Thus, first mathematical formulations of evacuation dynamics were closely related to mechanical or biological systems. Further extensions on the mathematical modelling suggested several levels of description. In this sense, the elements of the system could be macro-, micro- or mesoscopically defined (as shown in Figure 3.1). Therefore, the capability of the models for describing behavioural responses in evacuation dynamics has a direct dependence on the level of description of the system and the definition of the nature of interaction rules.

Modern models for evacuation dynamics require the consideration of psychological processes inherent to human behaviour. In particular, the cognitive process of *perception*. This new modelling paradigm reinforces an individual characterisation of each member of the studied crowd and promises more realistic results.

5.1.1 Implications to the Modelling of Evacuation Dynamics for Normal Situations

From the psychological point of view, human behaviour implies several mental processes of complex nature. The introduction of personal characteristics like age, gender, culture, personal preferences of the individual tend to increase the complexity of individual behaviour. Thus, the development of a model for evacuation dynamics in normal situations based on a psychological point of view requires several simplifications. The core idea of our model is sustained on the Ecological Theory of cognition suggested by Gibson [87, 88]. In accordance to this theory, human behaviour is directly influenced by the perceived surrounding situation. In particular, from those events and objects that the individual can see. In this sense, the mathematical formulation of our model considers three main aspects. First, the definition of *specific behavioural responses* relevant to evacuation dynamics in normal situations, here denoted as *controlled evacuations*. Second, the identification of the *inherent dependencies* among these responses. Together with the introduction of a *model for visual perception* as a manner of transformation of specific environmental data into the behavioural response.

1. ***Definition of behavioural responses in evacuation dynamics for normal situations***. In general words, the term *action* is a frequently used synonym to behavioural response. In the context of evacuation dynamics, *individual behaviour* refers exclusively to the action taken by the person

due a specific stimulus. Meanwhile, collective behaviour results from the transformation of actions into a general belief which is followed by all the participants in a group [224]. Thus, any action implies the transformation of the behavioural state according to the specific situation. For evacuations taking place in normal or emergency-scaled situations, the behaviour of the evacuating crowd is related to the formation of characteristic motion patterns. The present study is focused on the modelling of evacuations in normal situations and its corresponding dynamics. And for this purpose, each member of an evacuating crowd is modelled separately in terms of its position and walking direction $(\boldsymbol{x}, \theta)$.

2. ***Dependencies of behavioural responses***. As previously reviewed in Chapter 4, beyond its subjective aspects (like feelings, emotions or instincts) human behaviour obeys not only to internal but also to external factors. In particular to the surrounding environment (the Ecological Theory [87, 88]). Within the context of evacuation dynamics, the process of evacuation implies complex interactions among the individuals of the evacuating crowd and within the place where they are found. In this sense, the nature of these interactions do not only correspond to the influence of the behavioural responses of the other individuals but it also obeys to the presence of further obstacles in its vicinity (i.e., chairs, tables, sculptures). Thus, a deeper understanding of the manner how such influences take place has a central role in modern modelling of evacuation dynamics. In this work, the influence of these external factors in the behavioural dynamics of an evacuating crowd are considered.

3. ***Information-processing***. A further aspect in the development of our psychology-based model is the identification of all relevant processes implied in the response elaboration within evacuation dynamics. In the previous chapter the cognitive processes of *perception, attention* and *response elaboration* were generally reviewed. However, a standard procedure on the manner how the incoming sensorial input is transformed into a behavioural response does not exist. Moreover, the available cognition models are focused on their description and theoretical implications instead of the practical application. Thus, a computational implementation is not affordable in most of the cases. Regarding to evacuation dynamics, an individual behaves in a way which directly refers to the incoming information of the actual situation. Then, any further change on its behaviour is originated by a change of the surrounding or individual goals. Therefore, *visual perception* is relevant for modelling evacuation

dynamics as a manner of how individuals receive updated information from their surrounding. In this sense, a simplified model for visual perception in evacuation dynamics is developed and presented in this work (Section 5.1.6).

5.1.2 Individual Response in Evacuation Dynamics

In general terms, evacuation dynamics refers to the upcoming motion patterns which obey the walking path described by each individual in its way to the exit. However, this self-formed path do not only depends on several interactions of the individual with its environment but also on the situation which is being experienced (Section 3.1.2). In this sense, characteristic self-formation motion patterns distinguish an evacuation given in a so-called *normal situation* from another when an emergency occurs, especially to *panic-scaled situations*.

Evacuations during a normal situation (*controlled evacuations*) have, in general, the following characteristics:

- Individuals have *specific goals* to achieve during the evacuation. For instance, to arrive to an specific place or to follow a predefined evacuation route. However, changes in the desired evacuation route or taking detours are disliked. In cases where there is no predefined evacuation route, one may assume that the fastest known route is commonly taken. For example, to go out of the building by following the same route in which the person came in.

- Moreover, individuals tend to walk at *comfortable speed* or to *stop* in order to *avoid* possible *collisions* with other persons or objects. In the same way, individuals tend to keep a certain distance to other persons or objects *avoiding physical contact* (absence of *"pushing"* behaviour).

In opposition to this, evacuations during so-called panic-scaled situations occurs when the original emergency is not controlled within a short period of time or when the perceived emergency increases. This type of evacuations are generally distinguished on the following:

- Individuals present a tendency to *run*. As a result of this, *physical interactions* by means of pushing are present. Moreover, the formation of the so-called *"blind-actionism"* is commonly related to the growing nervousness experienced by the individuals.

- Eventual *herding behaviour* or changes on the original evacuation plan can take place due to *unexpected events* like locked doors or high concentration of persons. In the same way, ignorance of alternative evacuation routes or emergency exits may occur.

A common belief regarding to panic-scaled situations is the appearance of *competitive* and frequently *dangerous* behaviour within the individuals of the crowds. Contrary to this, Smelser [224] suggested the necessary presence of several factors (like psychological, sociological or physiological) which conduces to specific events, that without an interruption, may escalate into panic (Section 4.2.3).

System Definition and Behavioural Variables

As a first contribution, the present study focuses on the modelling of evacuations in normal situations, whose decisive characteristic is the *absence of physical force or pushing* among the individuals. In addition to this, individuals avoid possible collisions with other individuals or objects in its vicinity. In this sense, behavioural motion patterns inherent to evacuation dynamics in normal situations are here modelled by means of the position $\boldsymbol{x}$ and walking direction (θ) of each individual. These variables are here identified as the *state variables*, since they define the state of the "system" pedestrian at any time. In this sense, a crowd shall be also understood as "system" which is constituted by individuals. Moreover, the initial state of the system is defined by the initial position and walking direction of each individual, and is assumed to be known.

5.1.3 Model for a Single Pedestrian

At this point we will give an introductory example for motivating deeper considerations afterwards.

Example 1: Evacuation of a Single Individual. For illustrative purposes, an example of a *simple* evacuation scenario is shown in Figure 5.1. This scenario consists of one single room-building with one exit. Additional complexity is introduced by the presence of a fixed obstacle (big circle) inside the building-case. Finally one individual which is initially located inside the building shall evacuate the building-case. Figure 5.1 shows the initial state of the evacuation, here the starting position of the individual is exactly behind the fixed obstacle. In this way, there is no advantage among the direction taken by the individual (left or right). The walking direction of the simulated individual is represented

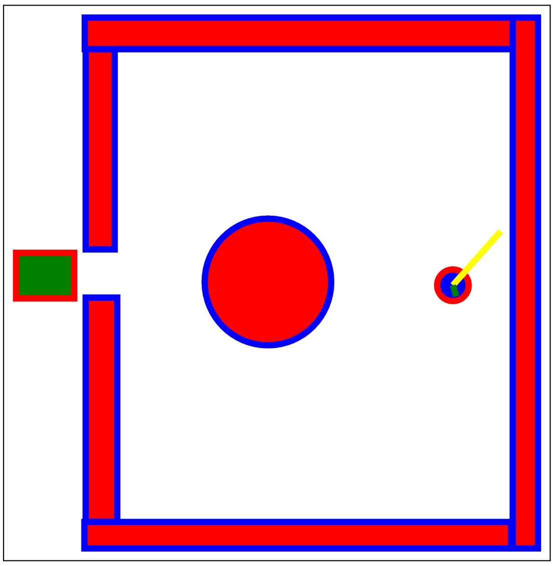

Figure 5.1: Example of a simple scenario. The fixed obstacle is represented as a big circle and the individual as a small circle.

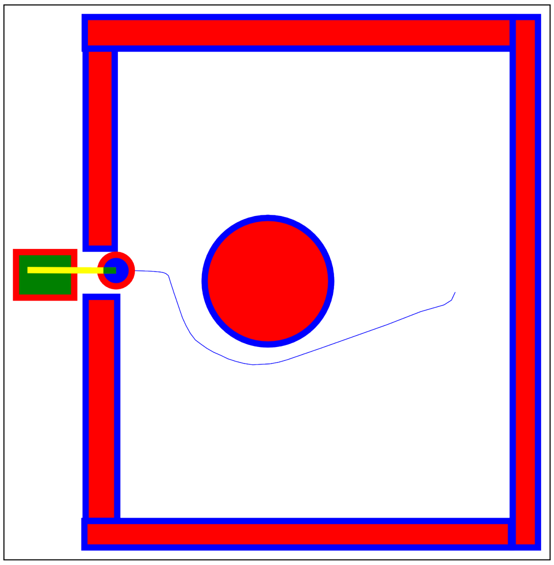

Figure 5.2: View of the evacuation route taken by the individual after 5 seconds of simulated time. The maximal walking speed of the individual was 1.4 m/s. Note the manoeuvre of collision avoidance.

by an arrow, as shown in both figures (5.1 and 5.2). As in real situations, individuals shall modify their walking direction in order to avoid possible collisions to other objects or individuals near to them. In this sense, Figure 5.2 shows the evacuation route taken by the simulated individual while avoiding its probable collision to the obstacle. Although the complexity of this example is relatively low, it underlines the following:

1. The motion path described by the individual gives a direct and possible way to the exit from its initial position. However, possible collisions shall be avoided by taking small detours. This is done when the individual makes small changes to its walking direction.

2. Complexity in the trajectory taken by the simulated individual is given due to the presence of an obstacle in its vicinity. This example illustrate, the influence of the environmental surrounding on the behavioural dynamics of an evacuation.

The Individual State

As mentioned before, we model the state of a pedestrian by means of two parameters:

- its position $\boldsymbol{x} \in \mathbb{R}^2$, and
- its walking direction $\theta \in (0, 2\pi]$.

The state of a single pedestrian is therefore modelled by the tuple $(\boldsymbol{x}(t), \theta(t))$, since the state changes over the time. The goal of the following description is to model the evolution of the state $(\boldsymbol{x}, \theta)$ over the time t. For notational compactness we will write s for the time-dependent state $(\boldsymbol{x}, \theta)$ and also write $\boldsymbol{x}$ and θ instead of $\boldsymbol{x}(t)$ and $\theta(t)$. Furthermore we write $s_{\boldsymbol{x}}$ for accessing the first entry of the tuple $(\boldsymbol{x}, \theta)$ and s_θ for the second entry. For modelling the continuous state-change of a system s, an ordinary differential equation (ODE) of first order is generally defined by a function F for the time derivative of the state s:

$$(\dot{\boldsymbol{x}}, \dot{\theta}) := \dot{s} := \frac{ds(t)}{dt} := F(x, t). \tag{5.1}$$

However, before proceeding with a specific definition of F, we introduce an abstraction for the context in which the pedestrian will be simulated: the scenario.

The Scenario. For modelling a pedestrian evacuating from a building, an important ingredient is the building itself, including its rooms, walls and furniture. In our model we assume these objects to be static. Thus, they do not move or change their state during the simulation. Even though dynamic objects inside a scenario can also be modelled with this framework, we reduce this explanation for simpleness and comprehensiveness.

Since a scenario (c) with all its objects inside is here assumed to be static, it only contributes constants. Thus, F can be defined as being dependent on the scenario (c) and on the state (s) by writing:

$$\dot{s} := F(s, c). \tag{5.2}$$

Due to the fact that, the scenario is static, the constants are eliminated and Equation 5.2 is written as:

$$\dot{s} := F_c(s) \tag{5.3}$$

The actual implementation of the function F_c with its dependency on “objects” and their position and shape is done with an Object-Oriented framework, detailed in Section 5.1.6.

Differential Equation for the State-change of a Single Pedestrian

Due to the lack of available differential equations with focus on perception in the literature, this work presents a first tentative model. Then, the model shall be understood as a *proof-of-concept* for the feasibility of such approach. Thus, the introduced functions are not based on previously known laws from literature, but emerged in an evolutionary process for finding a model which presents meaningful results. Future work shall consider meaningful adaptions to our in the following presented model. This section will now introduce an ODE for the state-change of a single evacuating pedestrian in a completely static environment. In this sense, Equation 5.3 is now defined as:

$$\dot{s} := F_c(s) := \left(F_c^{\boldsymbol{x}}(s), F_c^{\theta}(s)\right)^T \tag{5.4}$$

Function $F_c^{\boldsymbol{x}}$ is the part of F_c for computing $\dot{\boldsymbol{x}}$:

$$F_c^{\boldsymbol{x}}(s) := v(s) \cdot (\cos(s_\theta), \sin(s_\theta))^T \tag{5.5}$$

Function v computes the absolute velocity in direction s_θ as

$$v(s) := C_1 \cdot (1 - r(s)) \,. \tag{5.6}$$

C_1 is a model constant giving the maximal walking speed possible for the pedestrian. The term r is the *resistance* in the given direction evaluated at the given position, being $r : \left(\mathbb{R}^2 \times (-\pi, \pi]\right) \rightarrow [0, 1]$ the *resistance* function is modelled as:

$$r(\boldsymbol{x}, \alpha) := \exp\left(-d_{\min}(\boldsymbol{x}, \alpha)\right) \tag{5.7}$$

where $d_{\min}(\boldsymbol{x}, \alpha)$ depends inherently on the scenario (c) and computes the distance to the nearest object in direction s_α. The function F_c^{θ} is the part of F_c for computing $\dot{\theta}$ is chosen here as:

$$F_c^{\theta}(s) := C_2 \cdot (\alpha_{\text{opt}}(s) - s_\theta) \tag{5.8}$$

where C_2 is a constant for the rotation speed and $\alpha_{\text{opt}} : \left(\mathbb{R}^2 \times (-\pi, \pi]\right) \rightarrow (-\pi, \pi]$ is the so-called *desired direction* of the individual. In this direction the so-called *walkability* has a maximum, which is computed as follows:

$$\alpha_{\text{opt}}(s) := \text{maximizer}(w(s_{\boldsymbol{x}}, \alpha), \alpha \in [-\frac{\pi}{2}, \frac{\pi}{2}]). \tag{5.9}$$

Then, we define the walkability function $w : \left(\mathbb{R}^2 \times \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]\right) \rightarrow [0, 1]$ as follows:

$$w(s_{\boldsymbol{x}}, \alpha) := g(s_{\boldsymbol{x}}, \alpha) \cdot f(s_{\boldsymbol{x}}, \alpha) \tag{5.10}$$

here $g(s_{\boldsymbol{x}}, \alpha)$ computes the so-called *angular goal attraction* factor, which is chosen here as:

$$g(s_{\boldsymbol{x}}, \alpha) := \exp\left(-\sqrt{C_3 \cdot |\alpha_{\text{goal}} - \alpha|}\right) \tag{5.11}$$

where C_3 is a model constant for shaping the *goal attraction* and the term $|\alpha_{\text{goal}} - \alpha|$ denotes the angle between the direction of the goal (α_{goal}) and the direction α. Meanwhile, α_{goal} may be here assumed to be part of the scenario.

The second factor of the walkability function $f(s_{\boldsymbol{x}}, \alpha) : \left(\mathbb{R}^2 \times [-\frac{\pi}{2}, \frac{\pi}{2}]\right) \to [0, 1]$ giving a *walking freedom* depends upon, if the nearest object in the given direction α is static or another pedestrian. For the case with a single pedestrian, f is simply chosen as:

$$f(s_{\boldsymbol{x}}, \alpha) := \left(1 - \sqrt{r(s_{\boldsymbol{x}}, \alpha)}\right)^2 \tag{5.12}$$

where r is again the resistance previously defined in Equation 5.7.

However, until now only the mathematical view on the basic model for a single pedestrian has been presented. In the next section, the mathematical description of the behaviour of a crowd as a system of individuals is introduced.

5.1.4 Model for a Crowd

Again we will give an introductory example for motivating deeper considerations afterwards.

Example 2: Evacuation of a Group of Individuals. A more complex evacuation scenario is shown in Figures 5.3 and 5.4. Complexity is introduced by considering the evacuation of twenty individuals, instead of only one as in the first example.

As in the starting case, each individual has an initial position inside the building and should take a direct way to the exit while avoiding any possible collision with fixed obstacles or with any other individual. This new scenario increases the complexity of the task, since interactions among the individuals emerge and self-organisation manoeuvres shall take place. Moreover, the influence of the environment on each individual changes depending to its position and the way in which other objects (or individuals) surrounds it, as in reality occurs. In other words, the surrounding is dynamic.

From this example, we can underline the following:

1. Trajectories described by each individual are more complex than the one described in the example of the single individual. This complexity is due

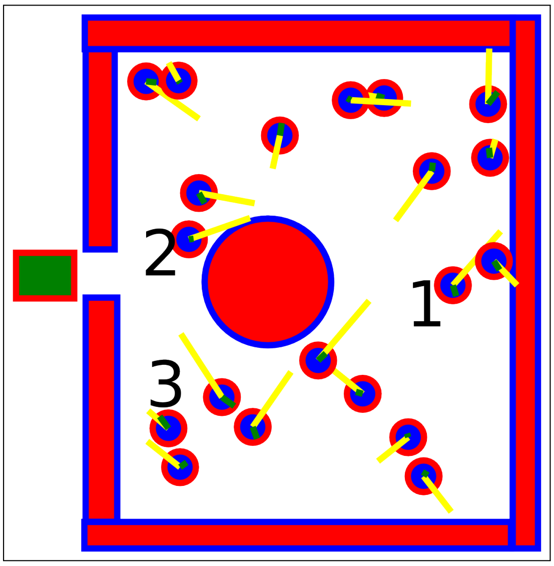

Figure 5.3: View of a more complex scenario containing one fixed obstacle (big circle) and twenty individuals (small circles).

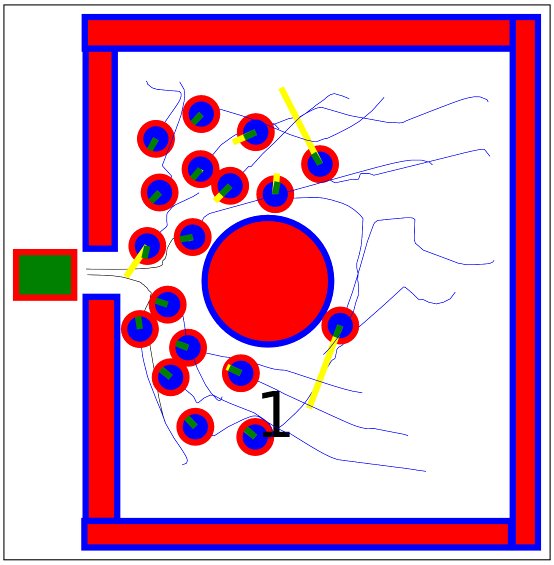

Figure 5.4: View of the evacuation route taken by the individuals after 5 seconds of simulated time. The individuals number 2 and 3 have already evacuated the room.

to the presence of further individuals. This situation carries out to several detour manoeuvres among the group by making small changes in their walking speed in order to avoid possible collisions.

2. Due to the close distance between some individuals, stopping manoeuvres take place. The walking speed of each individual is not constant and varies in order to avoid collisions to objects or other individuals close by.

3. Moreover, due to the reduction of walking speed and collision avoidance, the resulting interactions among the individuals produce, in this case, longer evacuation times. For instance, the simulated individual (number 1) has an initial position similar to the individual of the previous example. However, after 5 seconds of simulated evacuation time, the individual is still located inside the building of the new scenario.

Differential Equation for the State-change of a Crowd

At first we want to mention again, that the following ODE for modelling a crowd, is motivated by the lack of available models with focus on perception in literature. Then, the model shall be again understood as a *proof-of-concept* rather than a discovered natural law.

For the introduction of the state-change of a crowd, the previous declarations for the state of the system are extended in a way that it does not only describe the state of one, but the state of N pedestrians. This is done by redefining the state of the system as follows:

$$s := (s_1, s_2, ..., s_N)^T \in \mathbb{R}^{N\times 3}, \tag{5.13}$$

with:

$$s_i := (\boldsymbol{x}, \theta)^T \in \mathbb{R}^3. \tag{5.14}$$

In the same way as in Section 5.1.3, the change of the state of the system is reformulated as:

$$\dot{s} := F_c^N(s) \tag{5.15}$$

where F_c^N now depends on the state of all pedestrians. Hence the previous definitions require adaptations. At first some additional notational conventions are required in order to access the state of each individual from inside of our functions. In this sense, let

- $s_{i,\boldsymbol{x}}$ be the position $\boldsymbol{x} = (x, y)$ of the pedestrian i, and
- $s_{i,\theta}$ be the walking direction (θ) of pedestrian i.

From this, the change of the state of the system $\dot{s}$ is rewritten as follows:

$$\dot{s} := (\dot{s_1}, \dot{s_2}, ..., \dot{s_n})^T := F_c^N(s) := \left(F_c^1(s), F_c^2(s), ..., F_c^n(s)\right)^T. \tag{5.16}$$

note that F_c^i does again depend on the complete state of the system. Hence the individual response depends on the others state. Moreover, the time derivative of the position and walking direction shall be defined for each individual separately. In this sense, let:

- $F_c^{i,\boldsymbol{x}}(s)$ computes the individual velocity $\dot{\boldsymbol{x}}$ of pedestrian i, and
- $F_c^{i,\theta}(s)$ computes the individual rotation speed $\dot{\theta}$ of pedestrian i.

In addition to this and for the reuse of previous definitions, some concepts shall be generalised.

$$F_c^{i,\boldsymbol{x}}(s) := v^i(s) \cdot (\cos(s_{i,\theta}), \sin(s_{i,\theta}))^T \tag{5.17}$$

with:

$$v^i(s) := C_1^i \cdot (1 - r(s_{i,\boldsymbol{x}}, s_{i,\theta}, s|_{\neq i})) \tag{5.18}$$

where $|_{\neq i}$ shall restrict s to all entries but the ith. The reformulation of the *resistance* is:

$$r : \left(\mathbb{R}^2 \times (-\pi, \pi] \times \mathbb{R}^{(n-1)\times 3}\right) \rightarrow [0, 1] \tag{5.19}$$

with:

$$r(s_{i,\boldsymbol{x}}, \alpha, s|_{\neq i}) := \exp\left(-d_{\text{min}}(s_{i,\boldsymbol{x}}, \alpha, s|_{\neq i}\right) \tag{5.20}$$

where d_{min} again depends inherently on the scenario (c) and computes the distance to the nearest object in direction α, but now including the other pedestrians in the evaluation. Note that C_1^i in Equation 5.20 has an index i, hence each individual may have an individual maximal walking speed. Now the individual *rotation speed* $F_c^{i,\theta}$ is reformulated as:

$$F_c^{i,\theta}(s) := \left((\alpha_{\text{opt}}(s_{i,\boldsymbol{x}}, s_{i,\theta}, s|_{\neq i})) - s_{i,\theta}\right) \cdot C_2^i \tag{5.21}$$

where $\alpha_{\text{opt}} : \left(\mathbb{R}^2 \times (-\pi, \pi] \times \mathbb{R}^{(n-1)\times 3}\right) \rightarrow [0, 1]$ is again the so-called desired direction now defined as:

$$\alpha_{\text{opt}}(s_{i,\boldsymbol{x}}, s_{i,\theta}, s|_{\neq i}) := \text{maximizer}\left(w(s_{i,\boldsymbol{x}}, s_{i,\theta}, s|_{\neq i}, \alpha), \alpha \in [-\frac{\pi}{2}, \frac{\pi}{2}]\right). \tag{5.22}$$

The walkability function $w : \left([-\frac{\pi}{2}, \frac{\pi}{2}] \times \mathbb{R}^2 \times (-\pi, \pi] \times \mathbb{R}^{(n-1)\times 3}\right) \rightarrow [0, 1]$ is chosen here as follows:

$$w(s_{i,\boldsymbol{x}}, s_{i,\theta}, s|_{\neq i}, \alpha) := g(s_{i,\boldsymbol{x}}, \alpha) \cdot f(s_{\boldsymbol{x}}, s_{i,\theta}, \alpha, s|_{\neq i}). \tag{5.23}$$

Here the function $g(s_{i,\boldsymbol{x}}, \alpha)$ can be reused from its previous definition in Equation 5.11. Meanwhile, $f(s_{\boldsymbol{x}}, s_{i,\theta}, \alpha, s|_{\neq i})$ which is again the *walking freedom*, needs to be modified as

$$f : \left(\mathbb{R}^2 \times [-\frac{\pi}{2}, \frac{\pi}{2}] \times \mathbb{R}^{(n-1)\times 3}\right) \rightarrow [0, 1].$$

For this, a distinction of two cases is made in our model to enforce the avoidance of collisions with pedestrians walking across: *a)* if the nearest object is static, and *b)* if the nearest object is a pedestrian, which follows:

$$f(s_{\boldsymbol{x}}, s_{i,\theta}, \alpha, s|_{\neq i}) := \begin{cases} \left(1 - \sqrt{r(s_{i,\boldsymbol{x}}, \alpha, s|_{\neq i})}\right)^2, & \text{if nearest object is static} \\ \left(C_4 \cdot r_{\boldsymbol{x}} + (1 - C_4) * (1 - r(s_{i,\boldsymbol{x}}, \alpha, s|_{\neq i}))\right), & \text{else} \end{cases} \tag{5.24}$$

where C_4 is a weighting constant for the importance of $r_{\boldsymbol{x}}$, which is in turn the so-called *cross resistance*, being a resistance induced by other pedestrians walking across. $r_{\boldsymbol{x}}$ is chosen here as follows:

$$r_{\boldsymbol{x}} := 0.5 \cdot \left(-\left((\cos(\theta_{\text{goal}}), \sin(\theta_{\text{goal}})) \cdot (\cos(s_{j,\theta}), \sin(s_{j,\theta}))^T\right) + 1.0\right) \tag{5.25}$$

where the index j refers to the nearest pedestrian. Meanwhile, θ_{goal} is again the intrinsic goal direction of the pedestrian i.

Approximation for the Environmental Influence. As explained above, the behavioural response of an evacuating crowd is determined by the response of its individual members and corresponds to their behavioural response. In this sense, the behavioural dynamics of the "system" crowd has been defined mathematically in Equation 5.16, being F_c^N a model for the behavioural response. The model calculates the so-called *walkability* (Equation 5.23) $w(s, \alpha)$ as weighting function for possible walking directions α. The *walkability* depends on the direction to the goal (Equation 5.11), particular to each pedestrian. Therefore, it considers *personal-criteria* in the decision for a direction of walking and is in turn used to determine the desired direction (Equation 5.22). In this sense, each possible direction which could be taken by the individual in our model will be evaluated in such a way that the direction with a maximum *walkability* will be the direction taken by the individual (Equation 5.21). The *resistance* (Equation 5.20) used in the evaluation of the *walkability* corresponds to the natural opposition of an individual to follow a direction in which obstacles are present. Meanwhile, the *walkability* on the whole corresponds to the tendency of an individual to choose the closest possible direction to the exit while avoiding obstacles. In Figure 5.5 the walkability function is shown, where α is to be understood relative to the *goal direction* α_{goal} (when $\alpha = 0$, then α refers to the direction α_{goal}) and d_{min} is the distance to the nearest object.

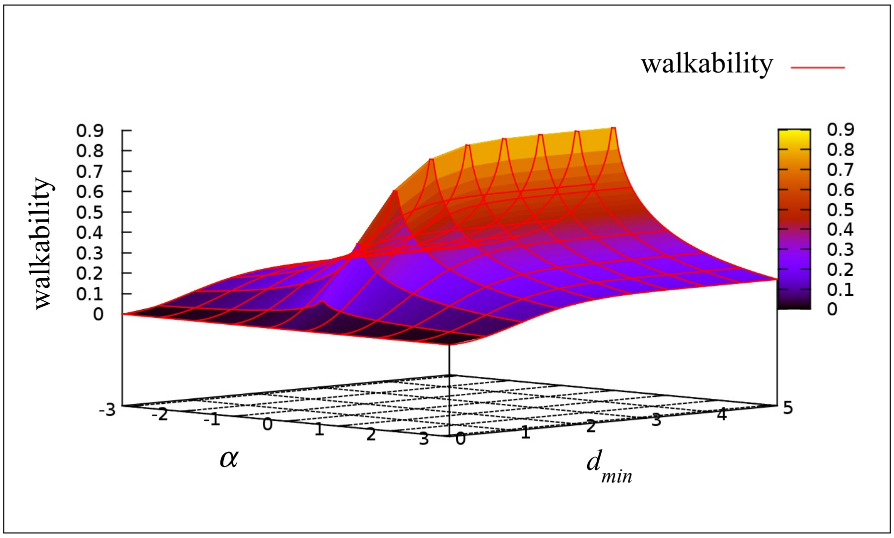

Figure 5.5: Graphical representation of the walkability function.

5.1.5 The New State of the System: Time Integration Scheme

As the reader might have recognised, the ODE defined for the state-change in Equation 5.16 might only be solved analytically for some special cases. In this section an integration scheme which takes advantage of the nature of the presented differential equation is introduced. In particular, an explicit Euler-scheme with Gauss-Seidel-like updates. For this purpose, we now extend Equation 5.15 with some initial values to become an *initial value problem*:

$$\dot{s} := F_c^N(s), \text{ with } s(0) = s_0 \tag{5.26}$$

here s_0 is the initial value, consisting of the position and walking direction of all pedestrians at time $t = 0$. Additionally, for computing a numerical solution of our system, a numerical scheme for computing the *resistance* $r(s_{i,\boldsymbol{x}}, \alpha, s|_{\neq i})$ (Equation 5.20) is required. In general terms, the *resistance* depends on the minimal distance to the nearest object in a direction α. For the determination of this distance, a ray-tracing with a modified ray form is adopted and introduced on page 90. At this point it shall be enough to mention that this scheme is used for determining the distance to the nearest object (in direction α) and therefore approximates the resistance numerically by sampling the field of vision of the pedestrian.

Explicit Euler-scheme with Randomised Gauss-Seidel-like Updates The idea behind the integration scheme presented in the following is simply, that we would be able to update the state of the individual i within a time step independently to the other members of the crowd, which would afterwards update their own state with respect to partially already updated and also old states (which are not updated yet). This proceeding is often referred as Gauss-Seidel-like updating. However, the proceeding has a non-negligible drawback in crowd simulation. The pedestrians are artificially numerated and if the order of the updates is constant, pedestrians with a higher index i in the state-vector would be always updated after the others. To avoid an influence like this, we introduce a randomisation of the update. For doing so, we define an index vector $I \in \mathbb{N}^N$, with N the number of pedestrians. This vector index I shall be initialised before the first time step with the ordered indexes $I_0 = (1, 2..., N)$. In the following algorithm we refer to a permutation operator P, which just applies a random permutation on its argument.

Algorithm 1 Euler Forward Time Integration Scheme with randomised Gauss-Seidel-like Updates

Euler-RGS-Forward (s, h, I)
$I = PI;$
for j=1,. . . ,n **do**
    $idx = I(j);$
    modified $= s(idx) + h \cdot F_c^{idx}(s);$
    if shape overlap **then**
        set previous $s(idx)$
        refine time step size $h = \frac{h}{2}$
        double time step number $n = 2n$
    end if
    $s(idx) =$ modified;
end for

5.1.6 Object-Oriented Model for Visual Perception

In general terms, the *Object-Orientation* (OO) is a modelling *paradigm* based on abstractions of real-world objects, being therefore a human-oriented methodology [184]. Thus, the development of an OO-model is based on a hierarchy of conceptual *abstraction*. In this sense, a complex system can be modelled by considering structured objects, their attributes and methods [4, 167].

In the context of evacuation dynamics, modern evacuation models imply the description of the behavioural dynamics of individuals pursuing an evacuation and their corresponding interactions. Examples of these interactions are the overtaking manoeuvres and collision avoidance with objects like individuals or obstacles. These interactions correspond to the inherent adaptation of the behavioural state of individuals to the situation in their vicinity. The behavioural dynamics of the system and the corresponding change of state were defined in Equations 5.13 and 5.16. The change of the state of the system does not only correspond to the individual adaptation manoeuvres due to the presence of individuals but also to the particular characteristics of the building of interest. These both sources comprise the function F_c^i. Thus, elementary factors proper to the architecture of the building of interest shall be considered and introduced.

Perceiving Pedestrian Evacuation Simulator – PerPedES

The Perceiving Pedestrian Evacuation Simulator (PerPedES) is an Object Oriented model built of two fundamental concepts: `Event` and `Shape`. The core statement of PerPedES is that everything within the modelled world is an *Event*. Therefore, the objects of the type `Event` model everything that is inside of a simulation scenario. In this way, all relevant objects of evacuation dynamics like the individuals of the evacuating crowd, exits and fixed obstacles are modelled with this abstraction. Figure 5.6 presents the hierarchy of the `Event`-model. The classes `PedestrianBase, Exit` and `Beamer` are all modelled as `Events`.

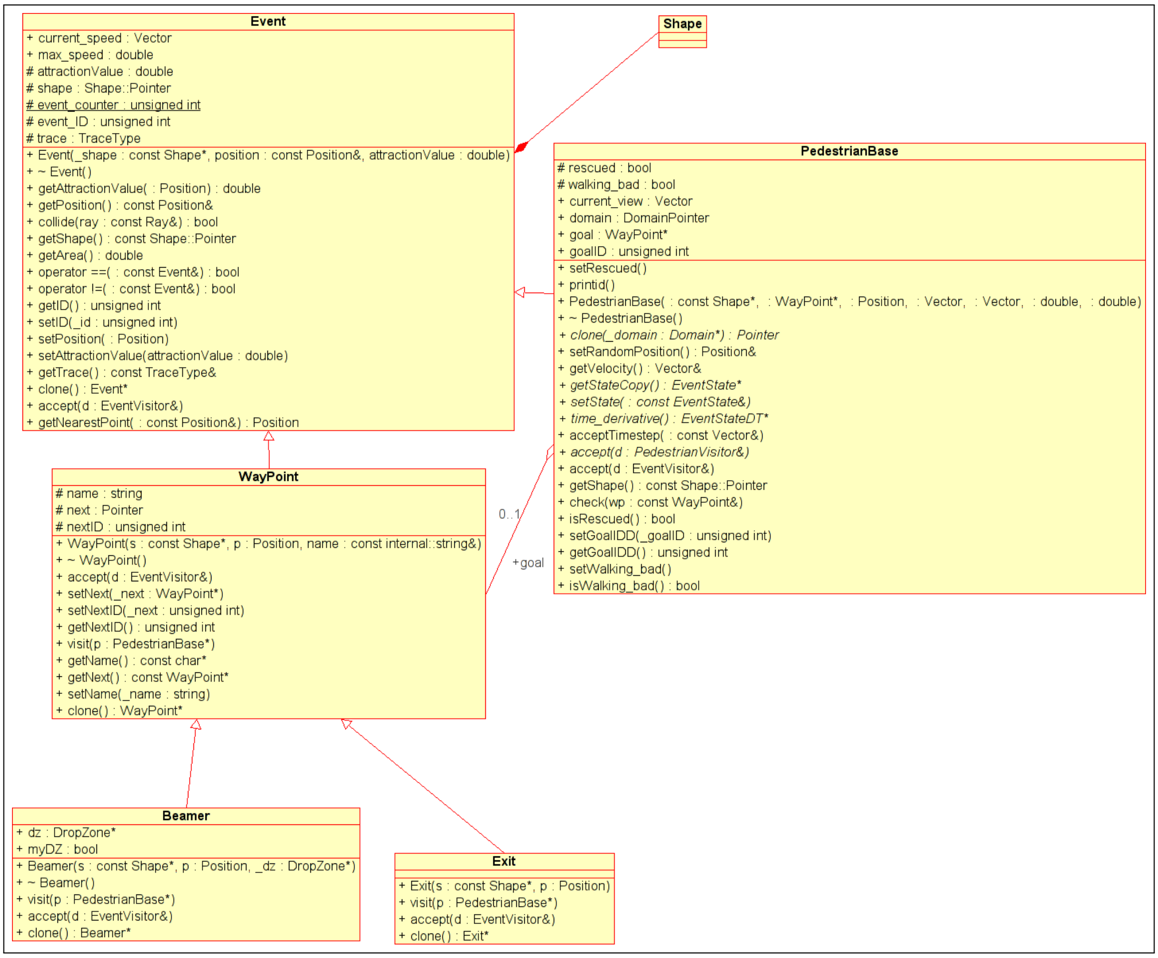

Figure 5.6: Hierarchical definition of the basic classes of the PerPedES event model.

Individuals of the evacuating crowd can be understood as *behavioural agents*, which are defined in this section. Beside its classification, real-world objects also have a physical shape. Figure 5.7 presents the geometry model within PerPedES Simulator, where the abstract class `Shape` and their specialisations `Segment, Rectangle` and `Circle` model geometrical objects used by the class `Event`.

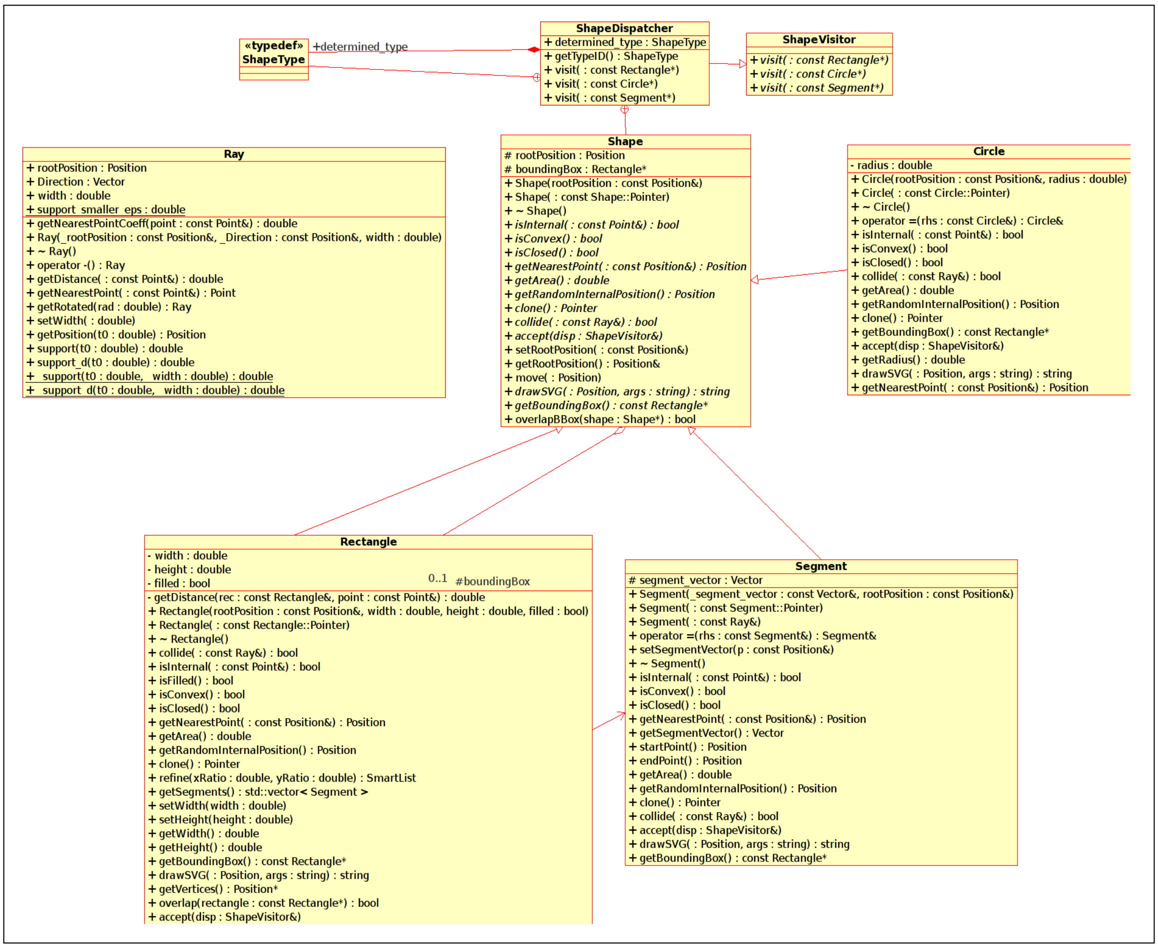

Figure 5.7: Hierarchical definition of the basic classes of the geometry model contained in PerPedES.

The *geometry model* of PerPedES is *polymorphic*, and therefore enables the execution of overloaded methods in a transparent way. In particular, `collide`, `getNearestPoint`, `getArea`. For the simplified identification of the type of objects, a so-called *dispatching-mechanism* has been implemented within the class `ShapeDispatcher`. Visual perception of pedestrians is approximated with the introduction of sampling rays (as explained on page 91). Such rays are modelled through the class `Ray`.

A Behavioural Agent. In computer science literature on software the term “(autonomous) agents” is commonly referring to a wide range of applications in many fields [84, 183, 216]. Thus an unique definition of *“agent”* may not be affordable. In the last decade, for instance, the term *software agent* was closely related to software “components” (or subroutines in its simpler form) which enable the communication between heterogeneous programs. This made possible the interoperability and exchange of information inside complex software and its several parts (programs and routines) [84]. In this sense, software developers tend to describe agents in terms of their environment, sensing capabilities, drives and actions [77].

In an abstract way, a software agent is here understood as a *computational entity* located (or embedded) in an artificial but specific *environment*. Each agent is autonomous from other agents but exists in the same scenario and communicates through its sensing capabilities and movement with its environment. In the modelling context of evacuation dynamics, these computational entities are here introduced as *behavioural agents*. Moreover, agents may be designed in a particular way so that each agent possess individual manners of action-taking for the fulfilment of specific goals or objectives. In PerPedES the behavioural agents are derived from the class `PedestrianBase` which is an `Event`. In this way, each agent inherits an attribute `shape` of type `Shape` and a position from `Event`. Additionally the attributes `goal` of type `WayPoint`, and direction are added to the agent. During the run of the simulator, the position, walking speed and target of the agent will change. Agents reaching an exit have finalised the evacuation of the building, and therefore are considered to be "rescued". In this sense, objects of type `Exit` take the behavioural agent out of the scenario once the agent has reached the simulated exit. Predefined evacuation routes for the studied building are modelled by means of objects of type `Waypoint`. Objects of the derived type `Beamer` have a specific target allocated within the `Domain` of the simulated building. The purpose of a `Beamer` is to move the behavioural agents instantly into the specific target. Both object types `Exit` and `Beamer` are `WayPoints` and therefore, they may be used as part of predefined evacuation routes. Thus, a global evacuation route is built by the connection of several allocations (i.e., local emergency exits, way-points, stairs and exits) distributed through the building and modelled by `WayPoints`. Further objects like walls, furniture and sculptures are considered to be fixed obstacles. Moreover, in contrast to `WayPoints` any possible collision with these obstacles shall be avoided. In PerPedES, obstacles are objects of the base class `Event`. Since PerPedES is object-oriented, all concept can be naturally extended and adopted to new requirements in modelling for a given scenario.

Visual Perception in Evacuation Dynamics

In general terms, the dynamical behaviour of a crowd during an evacuation results from the actions (behavioural responses) taken by the individuals of the crowd on their way to the exit. Then, each change of state over time is influenced by the surrounding and the behavioural responses of each individual in the crowd.

Approximated Visual Perception. Visual perception is a process of high complexity since it involves many "nearly instantaneous" sub-processes (e.g. eye movements, activation of brain regions, filtering of information, etc.) [35]. By means of this type of perception, individuals are able to recognise and to collect information of interest of its surrounding for its use in the elaboration of responses. In the context of evacuation dynamics, visual perception is relevant to the recognition of objects like emergency doors and signals, possible obstacles and persons. Thus, a simplified but specialised model for visual perception in evacuation process is introduced in this study.

The general idea of our proposed model for visual perception is illustrated in Figure 5.8. The scheme shows a individual P walking in the direction θ. Additionally, 3 (fixed) obstacles are also allocated in the same direction and are supposed to be "seen" by the individual. Then, the modelled individual shall modify its walking direction in order to avoid a collision with the obstacles. For this, the avoidance manoeuvre does not only depend on the recognition of the objects laying on the direction of walking, but also to the relative distance to them. For instance, D denotes the distance between the observed pedestrian P and the nearest obstacle allocated in θ direction.

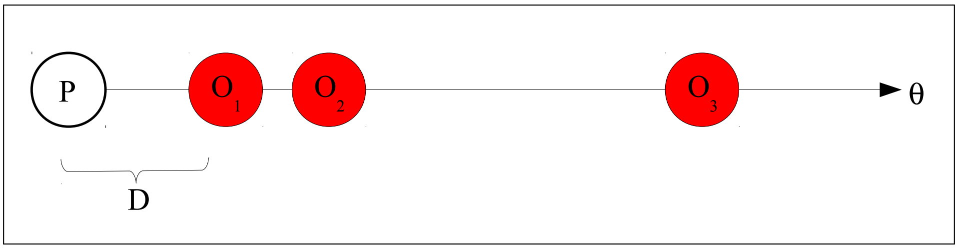

Figure 5.8: Simplified representation of visual perception of an individual P with walking direction θ. By this means the individual shall be able to "see" the obstacle O_1 which is the next to him in the same direction.

For the identification of the objects (i.e., further individuals and possible obstacles) laying in the direction of walking θ of an observed individual, we implement a modified ray tracing procedure. This method permits the recognition of objects laying in the vicinity of the observed individual and their relative distances, in a similar way to real visual perception.

In computer graphics, ray tracing is a widely used sampling technique for image generation. The technique is based on the track of the path described by a ray of light in an image plane by means of the virtual tracing through pixels. The purpose of this technique is the reproduction of diverse light effects (like shadowing) over an object of interest [92]. In the sense of optics, a ray is referred to a narrow beam of light. Meanwhile in mathematics, a ray is represented by a line segment with a starting point and a direction.

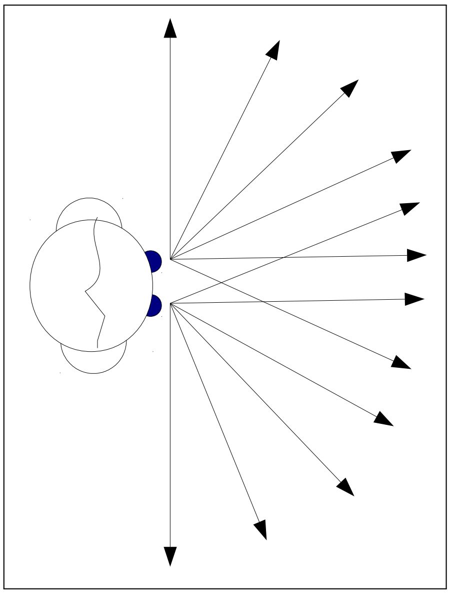

Figure 5.9: Simplified model of visual field for the identification of objects.

From this, an approximated model for visual perception may suggest the delivery of a infinite number of sampling rays in diverse directions. The rays have an equal starting point (the eyes of the modelled individual) but different directions. Constituting by this means the visual field of the individual, as shown in Figure 5.9.
Every object located inside the visual field will be then "sampled" by the rays when the object collides with it. A ray has an infinite length. Thus, several objects can be sampled by the same ray when they are located on the same direction. We do not consider reflections or absorptions as in computer graphics.

In the context of evacuation dynamics, modifications to the direction of walking and overtaking manoeuvres play a central role for collision avoidance. In this sense, the correct identification of objects lying in the vicinity of the pedestrian and the approximation of their relative distance are essential. In the

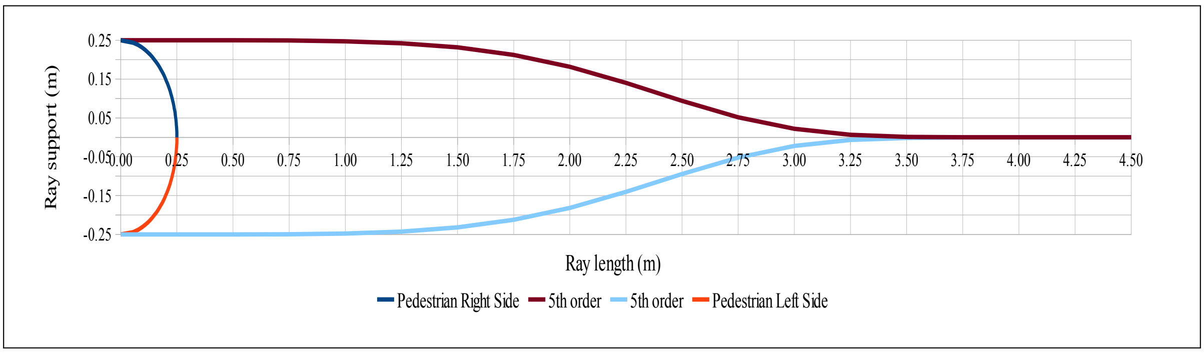

Figure 5.10: Modified sampling ray.

present study, a modified shape for the sampling ray, as seen in Figure 5.10, is introduced. The sampling ray modifies its shape as a function of the distance. The mathematical description of this ray in x-axis direction is given as follows:

$$y(x) = c_1 \exp\left(-c_2 x^n\right) \tag{5.27}$$

where $y(x)$ is denoted as support. Meanwhile, the term x represents the running ray. The coefficients n, c_1 and c_2 are shaping parameters (being $n = 5$ for this case). The visual field of the simulated individual, is then approximated with the generation of several sampling rays randomly orientated within 180° relative to the direction of walking of the simulated individual. In this way, the simulated individual will be more "sensible" to objects close to it than to those located far away. Meanwhile, all objects located "behind" the individual (and therefore, outside of the simulated field of vision) will not influence its walking direction.

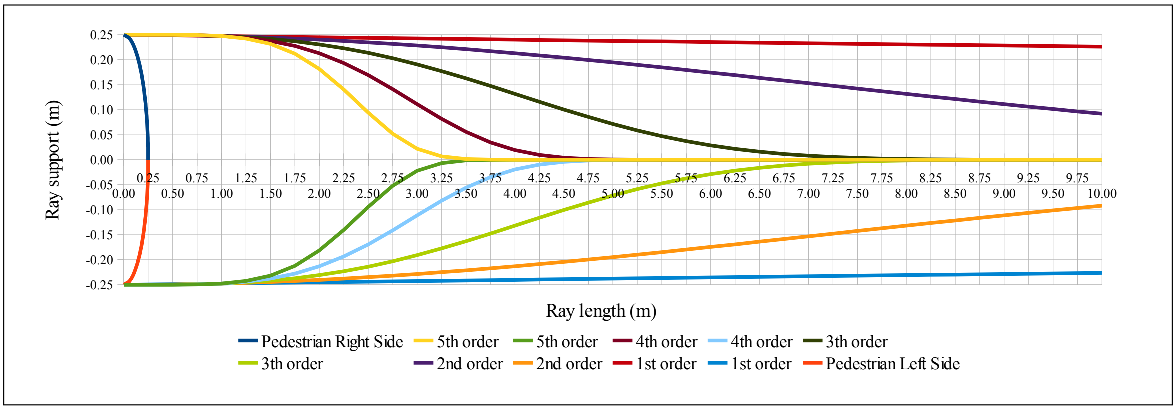

Figure 5.11: Example of modified rays and their corresponding support suggested for the simplified model of visual perception for evacuation dynamics.

In general terms, each ray is divided in two regions: one with high sensitivity and another with lower. The *sensible region* is the one which starts from the origin of rays and finishes when the support is almost zero. Generating by this means an area. The objects which lie at the inside of this area are more probable to be crossed by a sampling ray than those located outside of this area.

In this sense, Figure 5.11 shows the variation of the support of the ray with respect to the shaping parameter n. Moreover, the variation of the "quality" of the vision of a individual (i.e., short- and longsighted individuals) can be approximated by means of short or long sensible regions.

5.2 Tentative Validation of the Behavioural Model

Once the dynamics of a crowd within a so-called controlled evacuation have been mathematically formulated, the behavioural model shall be now validated. In general terms, the validation of a mathematical model pursues to guarantee the correct representation and reproduction of the behaviour shown by the real-world system of interest. In general, the qualitative validation of a mathematical model implies the comparison of labour experiments with simulated results. However, in the context of evacuation dynamics it is common that labour experiments occurs under simplified and highly controlled conditions. Thus, their results cannot always show real-world situations but an approximation to them. In this sense, the model validation based solely on experimental results is not always precise. The same occurs with validations considering specific events (like Mecca pilgrims, stampedes, panic-like behaviours), where the simultaneous occurrence of several influencing events introduces high complexity to the system and in most of the cases, such events cannot be easily isolated for its separate study.

In addition to this, the development of our mathematical model has been focused on the introduction of visual perception as the basis of the evaluation of the influencing factors on the behaviour of the individuals during a controlled evacuation. However, current literature in pedestrian and evacuation dynamics present a lack of differential equations with this focus. Then, the equations conforming the behavioural model (in pages 77 to 84) have been here newly developed and introduced. Thus, the validation of this model shall be first orientated to the proof-of-concept for modelling controlled evacuations based on this focus. In this sense, the present work proposes a tentative model validation based on the qualitative presence of motion patterns characteristic to this type of evacuations. In particular to the formation of arches due to blockages and stagnations at exits and bottlenecks, widely referred in current literature [115].

5.2.1 Characteristic Motion Patterns for Pedestrian Groups and Evacuation Dynamics

In the field of evacuation dynamics, current literature (as reviewed in Section 3.1.2) refers the presence of several motion patterns characteristic to pedestrian dynamics and common to real building evacuations (Table 5.1). In the present study, we suppose the formation of these patters (for instance, a bottleneck) to be dependent on the behavioural response described by the individuals (in particular, to their current direction and walking speed) and to the specific characteristics of the environment which surrounds him (e.g. presence of further individuals or fixed obstacles, location of available exits, etcetera). Then, the presence of these patterns within simulated scenarios shall permit a qualitative validation of our model.

Legend	Motion-pattern	Reason of formation
A	Arch-formation	Stagnations at exits
B	Clogging-effect	Stagnations at exits
C	Movement in-coordination	Bottlenecks
D	Lane-formation	Same walking direction
E	Overtaking-manoeuvres	Different walking speed
F	Collision-avoidance	Obstacles

Table 5.1: Examples of motion patterns characteristic to pedestrian dynamics and controlled evacuations, according to [115].

For the validation of the behavioural model, a test scenario has been modelled and introduced. Complexity in the test scenario is introduced in a way that simulated controlled evacuation within it shall reproduce real-world-like evacuations of a building of the same characteristics. In particular, the formation of characteristic motion patterns inherent to pedestrian dynamics and controlled evacuations. Figure 5.13 presents and identifies the motion patterns obtained according to the classification proposed in Table 5.1. In addition to this, simulation results shall be independent to the size of the time-step taken for the numerical solution of the model equations. Therefore, simulations shall present similar results (trajectories and upcoming motion patterns) when increasing time-step size. Results of these simulations are shown in Figures 5.12 to 5.15.

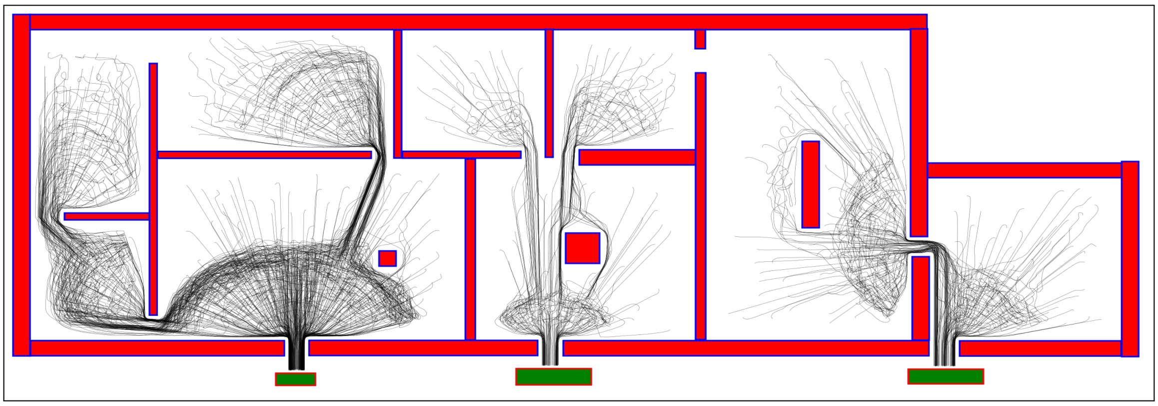

Figure 5.12: Resulting trajectories and motion patterns of test scenario with time-step dt=0.05 s.

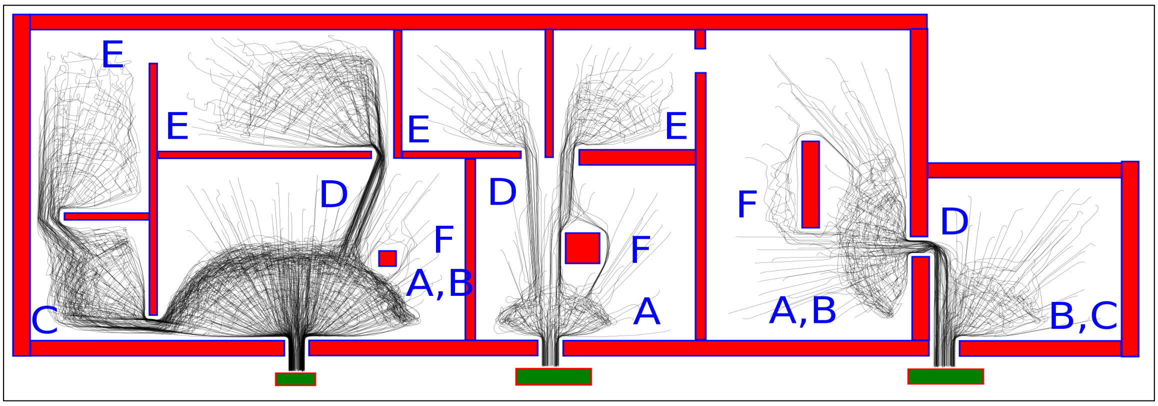

Figure 5.13: Resulting trajectories and motion patterns of test scenario with time-step dt=0.1 s.

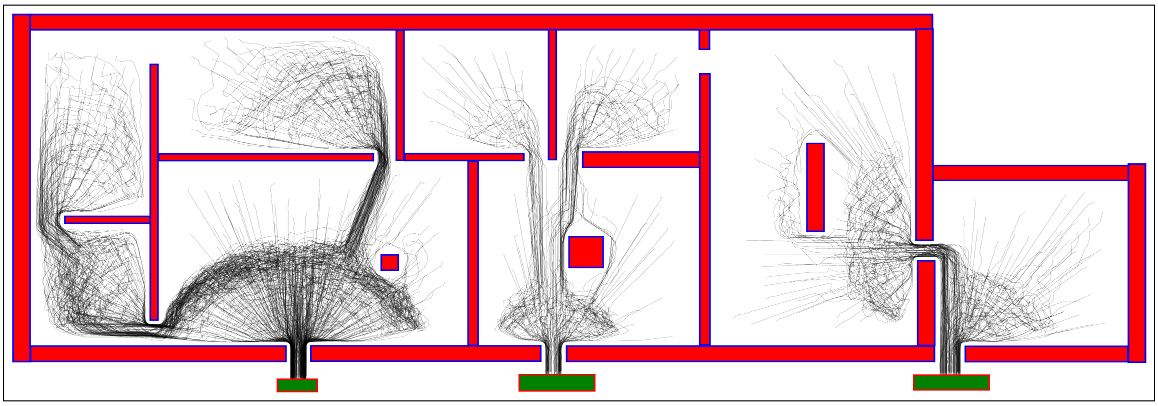

Figure 5.14: Resulting trajectories and motion patterns of test scenario with time-step dt=0.3 s.

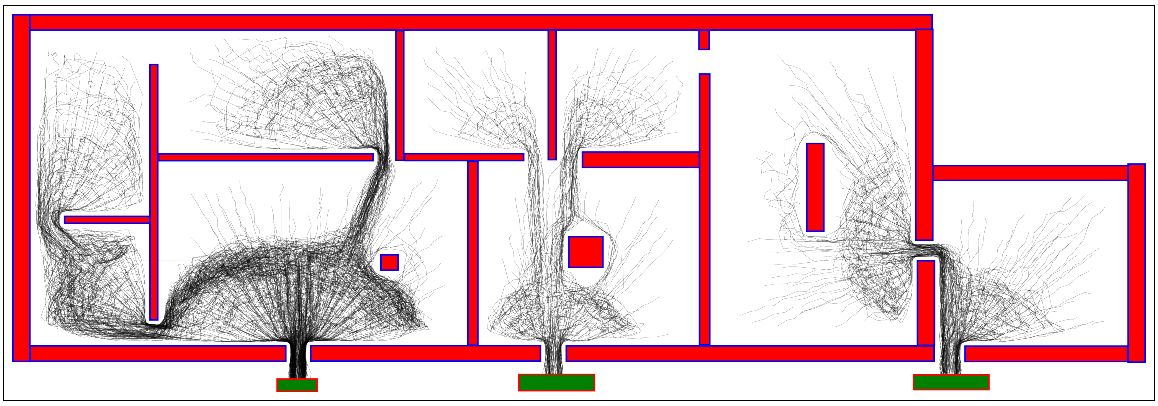

Figure 5.15: Resulting trajectories and motion patterns of test scenario with time-step dt=0.5 s.

5.2.2 Convergence of Numerical Solutions

A relevant aspect of numerical approximations is the *reliability* of the simulations. In general, a simulation is said to be reliable when the obtained results can be trusted. In other words, the simulation results shall be *consistent* with regards to arbitrary small time-steps. Mathematically, we refer to the stability and consistency of the numerical results. Moreover, when the numerical result fulfil stability and consistency criteria, we say that the approximated solution given by the result converges to the exact solution that we are looking for. Here, the stability of the numerical results obtained through PerPedES are tested. For this purpose, a representative evacuation scenario is required. The present study is focused in the analysis of evacuation dynamics within historic buildings. In particular, the Uffizi Gallery.

The studied gallery is located in an old Italian palace in the city of Florence. The exhibition area is distributed over the three-floor building, being the second floor where the majority of the works of art are exhibited. Thus, high concentrations of visitors are found in this area. Moreover, the works of art are classified in accordance to the epoch and to the artists which they belong. In this way, the works of art are distributed through the 43 exhibition-rooms of the second floor.

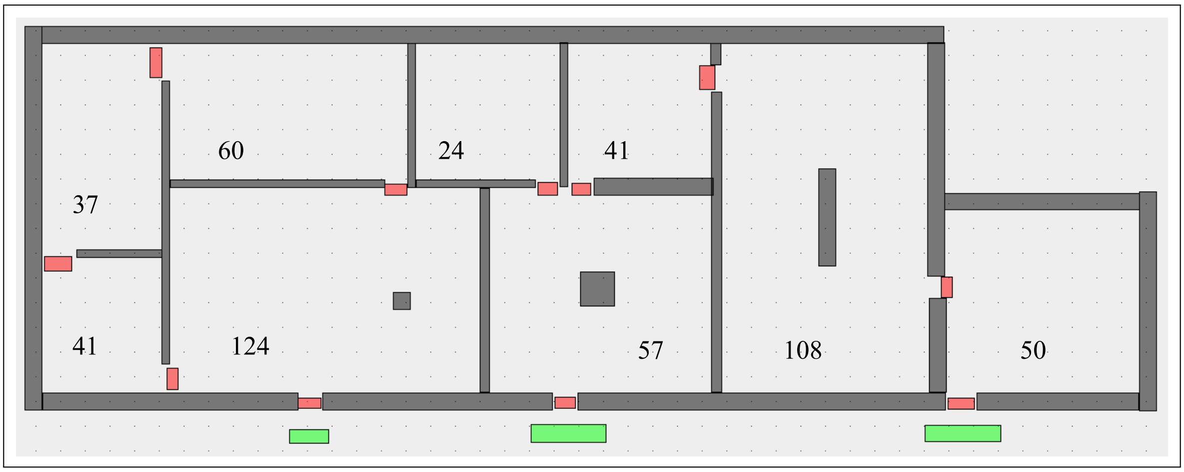

Figure 5.16: Test scenario taken for the study of stability in numerical results.

Due to the international relevance and acknowledge of the works of art and its artist, the exhibition rooms of the works of Botticelli and Leonardo da Vinci are of special interest to the visitors of the gallery. Moreover, in the context of evacuation dynamics interconnection among the different rooms and their degree of relevance are important aspects to consider for when selecting an evacuation route. In this sense, exhibition rooms number 2 to 15 located in the second floor of the gallery (shown in Figure 5.16) are taken as test scenario. For the test a total amount of 542 visitors are considered and distributed within the 9 exhibition rooms of the scenario. The amount of visitors per room is also shown in Figure 5.16. The considered visitors of the gallery are simulated by means of the previously described agents. The walls which conform each exhibition room are represented by means of interconnected grey rectangles. Way points and exits are represented with red and green rectangles, respectively. Moreover, isolated grey rectangles represent possible fixed obstacles for the visitors at the moment of an evacuation, like seating benches and sculptures. Initial state of the agents are given by its initial position and walking direction, which are randomly inserted. For each exhibition room a drop zone is defined, in which the position of the agents is equally distributed. The resultant evacuation times with respect to different time-step sizes (dt) are shown in Figure 5.17. Moreover, absolute error of the results obtained are shown in Table 5.2.

Time-step size (s)	Evacuation time (s)	Evacuation time (min)	Absolute error (min)
0.02	233.32	3.89	0.00
0.05	237.30	3.96	0.07
0.1	235.80	3.93	0.04
0.2	240.0	4.00	0.11
0.3	272.40	4.54	0.65
0.4	301.20	5.02	1.13
0.5	323.50	5.39	1.50

Table 5.2: Evacuation times obtained for the test scenario with respect to different time-step sizes and the corresponding absolute error of the results.

In this study, required evacuation times of specific scenarios are approximated by means of the purposed model. Special focus of the model is the introduction of visual perception as a manner to obtain information of the vicinity of each individual. Then any change of state experienced in the system will influence the change in the state of the individual.

The state change of the system has been defined in Equation 5.16, being F_c^N the environmental influence over the behavioural response. This function is approximated by means of the purposed visual perception model. Thus, the exact solution to the mathematical problem is not known. Therefore, the stability of the numerical results obtained are analysed in this work in a plausible sense. In other words, a numerical result is called to be stable if its absolute error decreases (in a consistent way) as the selected size of the time-step decreases.

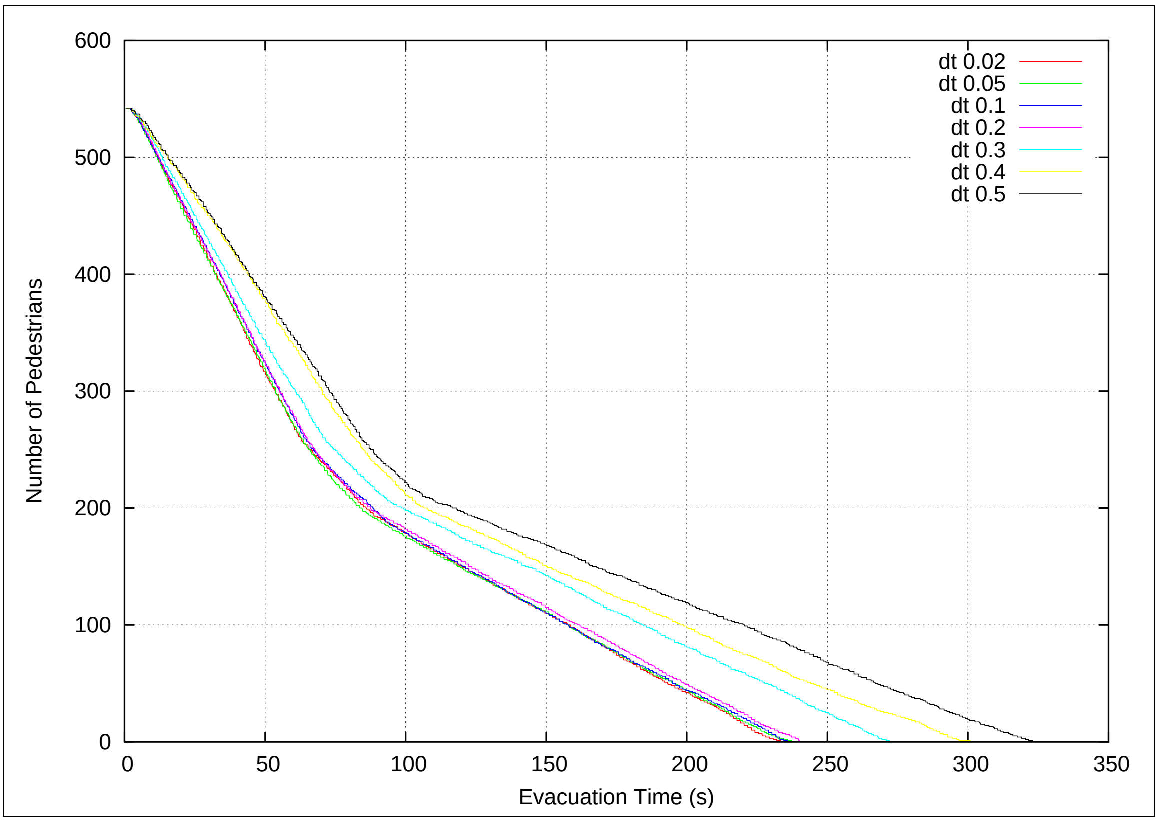

Figure 5.17: Simulated evacuation times obtained considering several time-step sizes.

Evacuation times for the scenario test present no significant difference by reduced size of time-steps, as shown in Table 5.2 and Figure 5.17. In particular for time-steps smaller than 0.2 seconds. Meanwhile, higher time-steps introduces numerical instability in the system, which are traduced into longer evacuation times. In this sense, we can say that the numerical results are consistent with regards to the time-step chosen. Meanwhile, stability is referred to those results which present small absolute errors. In this sense, a difference lower than ten seconds in the obtained evacuation time is considered negligible. Thus, numerical convergence can be assured for simulations with a selected time-step size not higher than 0.2 seconds.

5.2.3 Computation Time

A state-of-the-art problem with regards to numerical approximation is the achievement of convergence without high computation time. In general terms, numerical stability is frequently assured by small time-step sizes. However, this procedure increases in a significant way the computation time of the simulation. In our test scenario, stability of the numerical results is assured for time-step sizes of 0.2 seconds and below. This is translated into long simulation times, which a half time-step doubles the computation cost as shown in Figures 5.18 and 5.19. After a certain time of the simulation has past there are less pedestrians in the scenario. Thus, less computations are required and therefore the computation time required per time-step is reduced asymptotically (see Figure 5.18).

Moreover, for the computation of perception within PerPedES, ray tracing and their related processes are mostly computation time-consuming. However, an accurate approximation of visual perception requires a big number of rays. For this purpose, computation time of the test scenario regarding to the selection of the amount of generated sampling rays is given as follows. Figure 5.20 shows the simulated evacuation times obtained with regards to the number of sampling rays generated for each agent, where significant differences within the obtained evacuation times can be found by small number of generated sampling rays. In particular, for numbers lower than eight rays. Thus, high accuracy in the results is assured for scenarios with at least eight generated rays. The computation cost due to the amount of sampling rays, presents a similar behaviour to than shown for different time-step sizes, where the computation time increases linearly to the amount of sampling rays. An asymptotic reduction of the computation time is observed by long simulation times, due to lower amount of pedestrians in scenario (see Figure 5.21).

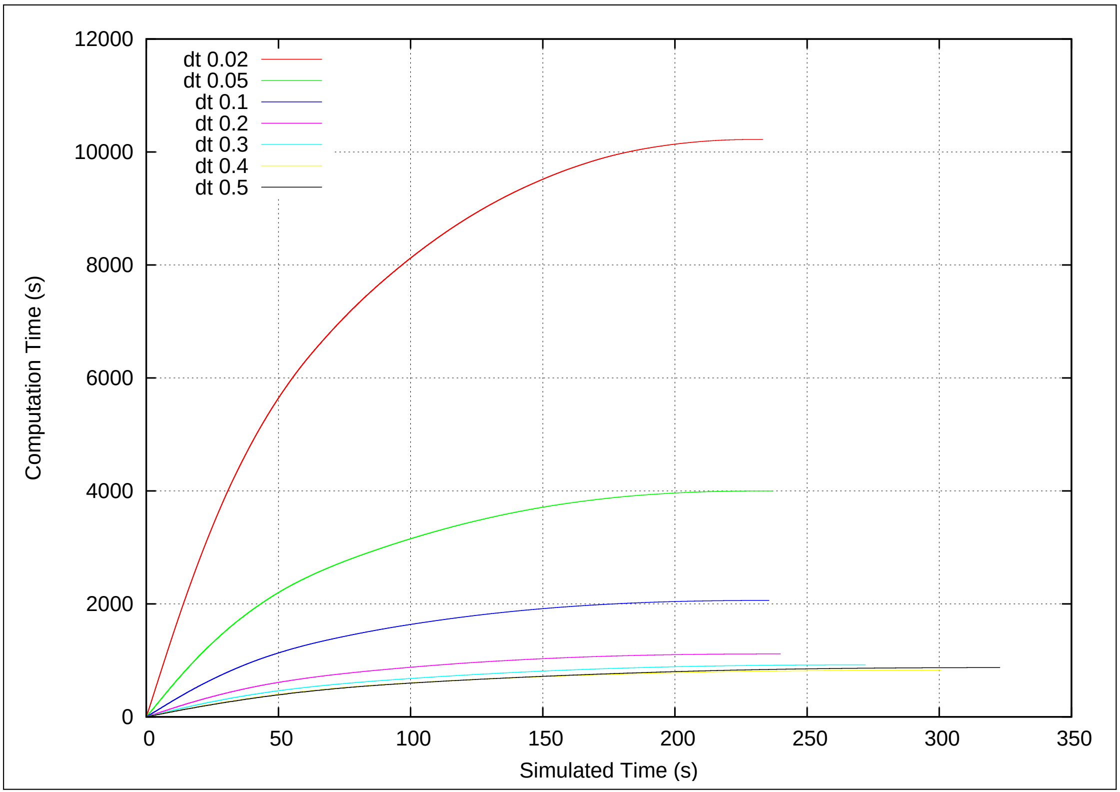

Figure 5.18: Computation time required for different time-step sizes on Intel E5530@2.4GHz CPU.

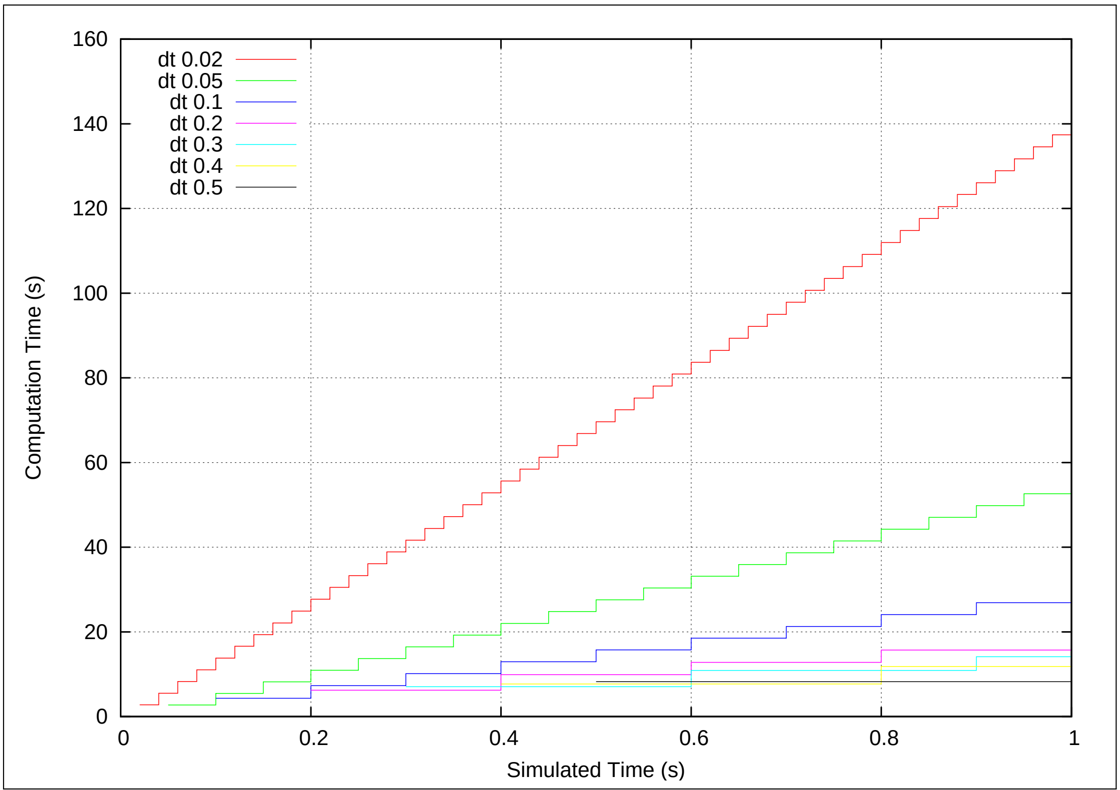

Figure 5.19: Computation time required for different time-step sizes within the first second of simulation on Intel E5530@2.4GHz CPU.

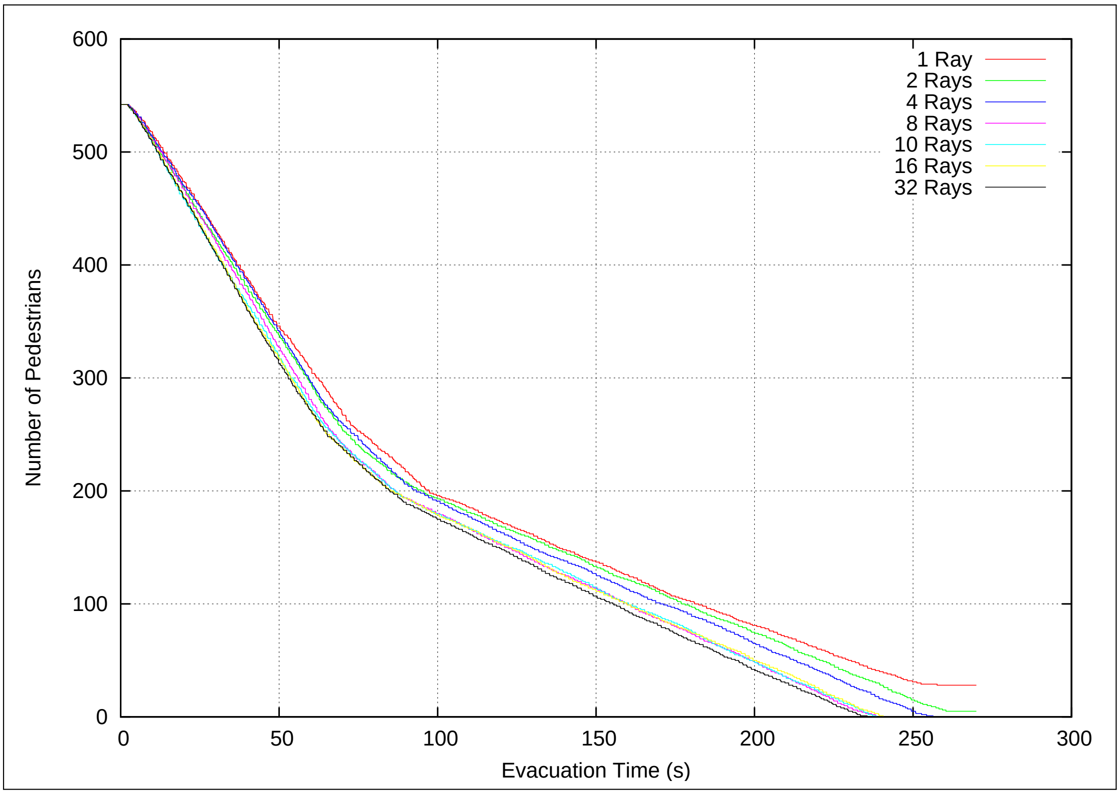

Figure 5.20: Simulated evacuation times obtained by varying the number of sampling rays.

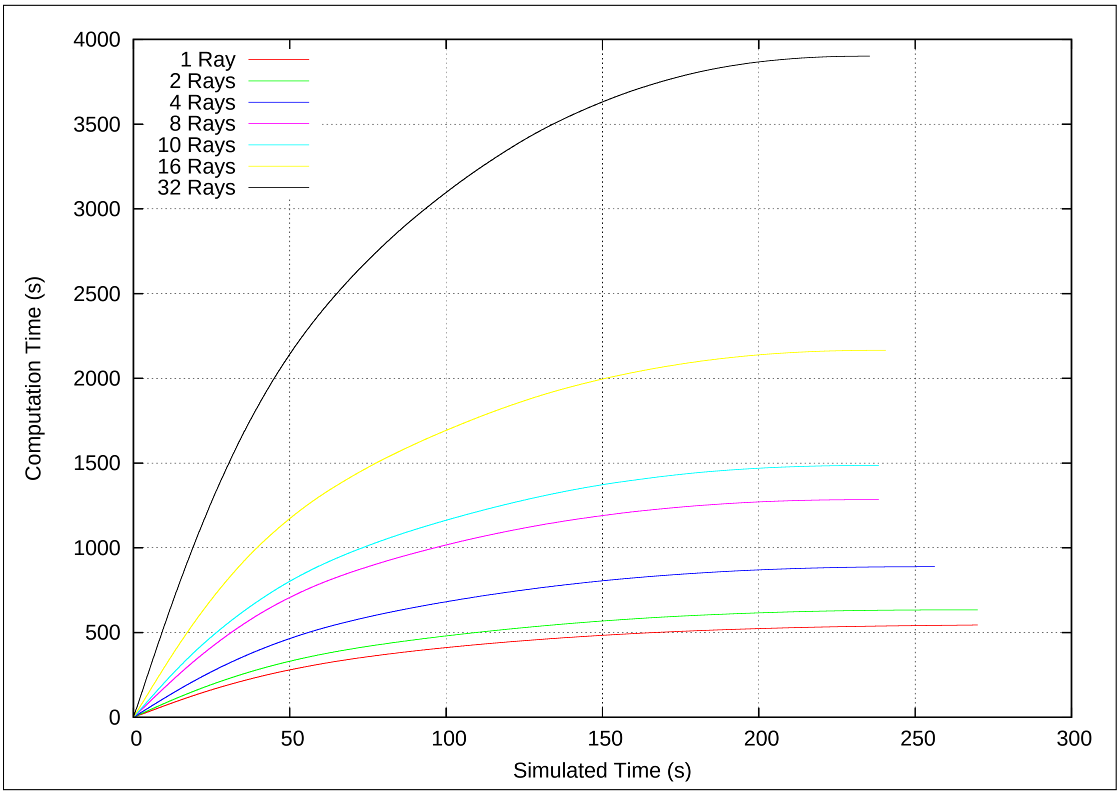

Figure 5.21: Computation time required for different number of sampling rays on Intel E5530@2.4GHz CPU.

5.3 Capabilities and Limitations of the Behavioural Model

The behavioural model introduces a novel approach for the modelling of evacuation dynamics in normal situations based on perception. Due to the lack of available differential equations with focus on perception in the literature, this work presents a first tentative model. Thus, the model shall be understood as a proof-of-concept for the feasibility of such approach. In general terms, the model: (i) allows single characterisations of the physiological attributes (in particular the averaged body-with and maximal walking speed) of the individuals of the evacuating crowd, (ii) describes the global dynamics of an evacuation by means of individual states, (iii) defines the changes of behavioural states (defined by means of the position and the walking direction of each individual) to be the resultant adaptation to the surrounding environment, (iv) introduces an individual psychology-like decision criteria (based on resistance and walkability factors) for the selection of an evacuation route, (v) reproduces characteristic self-organisation represented in the form of motion patterns inherent to pedestrian dynamics, and (vi) permits further extensions in the decision criteria for the individual selection of evacuation routes.

Moreover, visual perception is introduced by means of an Object-Oriented model, the so-called OO-visual perception model (previously explained in Section 5.1.6). In addition to the behavioural model, the OO-visual perception model: (i) introduces a simplified modelling approach based on abstractions of the real-world (for instance, individuals have been modelled as behavioural agents), (ii) introduces modularity and polymorphism in a sense that each object is an independent but interacting entity, and (iii) permits further modifications and extensions of the implemented methods.

Regarding to the validation of the model: (i) the resulting traces of the simulated evacuations present similar characteristics to motion patterns described in literature. In particular, arch- and lane-formations, clogging-effect, movement in-coordination, overtaking- and collision-avoidance manoeuvres (see Figures 5.12 to 5.15). (ii) Moreover, the obtained numerical results present consistency to small time-steps. Meanwhile, convergence of the results is assured by time-step sizes below 0.2 seconds and for an amount of eight sampling rays or higher (Figures 5.17 and 5.20).

The behavioural model has two major limitations: (i) the formation of artificial blockages due to so-called deadlocks (Figure 5.22), and (ii) the production of evacuation-artefacts due to the way-points model (Figure 5.23). In general terms, a *deadlock* refers to a repetitive situation without end. In computer science, a deadlock consist to a situation in which several competing actions are waiting for the fulfilment of the others, but due to specific factors, neither of the actions finishes their own task therefore non of the others do.

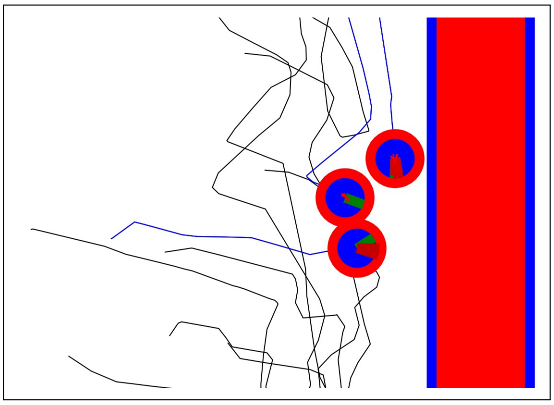

Figure 5.22: Example of possible deadlock-formation among behavioural agents.

In the behavioural model, a deadlock may take place due to the following situations: (i) collision avoidance due to opposite walking directions of the agents but a possible change in the walking direction is limited due to small distances between the agents or the presence of a wall or further obstacles close to the agents, and (ii) due to blockages among several agents due to high resistance values in all possible walking directions, within the field of sight.

Deadlock shown in Figure 5.22 is the result of both situations. The desired walking direction of the three agents produces a possible future collision among them and is avoided. Thus, no further "step" in front is allowed. Moreover, each agent is able to change its direction within 180° (90° at the left and the right of the agent in the direction of walking). However, everything that is allocated "behind" the agent is not perceived. In this sense, the agents shown in the figure can only perceive the other two agents and the wall.

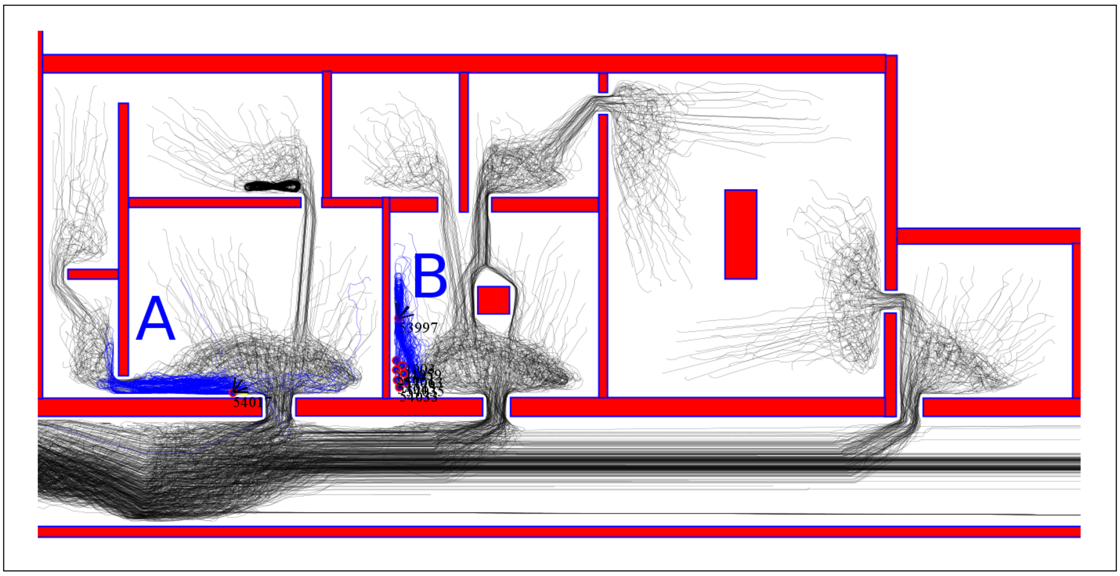

Figure 5.23: Example of evacuation-artefacts.

Artefacts in the simulated evacuation are artificially produced when the agent looses the next way-point because of (i) collision avoidance manoeuvres, and (ii) blockages at the exits.

Figure 5.23 presents an example of evacuation-artefacts produced by a lost of the way-point because of collision avoidance (Example A) and blockages at the exits (Example B).

The behavioural model is focused on modelling evacuation dynamics in normal situations. Thus, generation of forces in a sense of "pushing-behaviours" similar to those present in panic-like or emergen-cy-scaled situations (which may loose possible blockages at the exits) are not considered in the model. In this sense, further improvements are required. In particular, for the minimisation of deadlock-formations and evacuation-artefacts. Possible extensions of the agent geometry (for instance, into an ellipse-based geometry) seems promising since it enables rotation-effects of the agents. By this means, possible deadlocks and blockages at the exits could be avoided. In addition to this, further specialisation of the walkability function shall introduce additional influencing factors. For instance, the introduction of psychological-stress-based functions as well as the introduction of a short-term-memory-like procedure for the recognition of past way-points.

Chapter 6

Simulations and Numerical Results

In the context of risk management in the built environment, the behavioural model (PerPedES) is used for simulating evacuations in normal situations. Due to the particular limitations to the adaptation of the infrastructure of the building to modern safety standards and regulations, this work focuses on the study of evacuation dynamics in historic buildings. In particular to the Uffizi Gallery. In this context, diverse national safety regulations and norms applicable to modern and historic buildings located in the territory of Italy (i.e., occupational health and safety, fire prevention and protection and available certifications) are summarised in Section 6.1.1. Moreover, for the particular case of the Uffizi Gallery Section 6.1.2 presents a short review of the historical and cultural relevance of this gallery. In addition to this, within the context of risk reduction this study contributes to the analysis of vulnerability quantification for occupants inside buildings. In this sense, the demographic characteristics of the common visitors to the gallery are relevant for this purpose. For the simulation of realistic scenarios, the total amount of visitors of the gallery for the years 1996 to 2009 was analysed and classified based on the type of registered tickets (shown in Section 6.1.3). Moreover, Section 6.2 presents the particular aspects which influence the level of vulnerability of occupants of a historic building when pursuing an evacuation. Numerical results of simulations including evacuation times, distribution of individual walking speeds, trajectories and upcoming motion patterns of the simulated evacuations are presented in Section 6.3.

6.1 Historic Buildings: Case Study

A common characteristic of historic buildings, in comparison to modern ones, is the difficulty to adapt their conditions to modern safety regulations, fire protection and evacuation routes. In contrast to this, modern building design is in close relationship to modern regulations, where in early phases of its development, additional modifications to the original architectural concept may take place. In this sense, elevated construction costs in posterior stages may be avoided. Moreover, further aspects like the behavioural response of the structure of a modern building to specific events (i.e., fire, earthquakes) are known, obtainable or at least understood.

In this study, historic buildings are of special interest due to their significant cultural and historic value. This particular situation commonly implies restrictions (or even avoidance) regarding modifications to original architectural shape. Thus, in the context of safety inside buildings, further non-destructive alternatives shall be considered in order to preserve its heritage but without decreasing the safety-level of the visitors.

A further aspect of our interest, is the actual use given to historic buildings, which in most cases differs from the original concept for which the building was constructed. This is, antique buildings which originally belonged to families, were commonly used for private purposes (i.e., seasonal residences, familiar galleries, etc). However in actual days, many of these buildings do not belong to a particular family anymore or were donated for public interests (e.g. schools, universities, libraries, governmental offices, hospitals, theatres and museums). This situation is common to Europe and frequently implies modifications and adequations to the current situation of the building of interest. In this sense, the present study takes the Uffizi Gallery as case of study.

6.1.1 Historic Buildings and Safety Requirements

Safety inside of buildings is commonly referred to the application of diverse measures (in special due to fire protection and prevention) as a manner to guarantee the physical integrity of the occupants of the building of interest. These measures are typically contained in several national and international regulations, where a general overview is given in Section 2.1.2 of this study. However, a correct application of these regulations in specific cases – like in historic buildings – is limited due to the nature of such regulations. This is, fire protection and prevention norms tend to be general guides with concrete specifications to be fulfilled by almost any type of modern building. However, due to the particularities of historic buildings, most of such specifications are not applicable or may be in opposition to the norms of conservation and protection of cultural goods and heritage [7, 8, 155].

For the case of Italy, the number of norms and regulations relevant to fire protection and prevention of modern buildings is broad and in some cases they may contradict. This situation also applies to the particular case of historic buildings. This section presents a summary of the most relevant Italian norms and regulations with actual application to modern buildings together with specific norms applicable to historic buildings. For a better comprehension, these norms and regulations are classified according to their field of application and relevance. The summary is shown as follows.

Occupational Health and Safety Regulations

- **Decreto Ministeriale del 16/01/1997** (G.U. del 03/02/1997 n. 27): "Individuazione dei contenuti minimi della formazione dei lavoratori, dei rappresentanti per la sicurrezza e dei datori di lavoro che possono svolgere direttamente i compiti del responsabile del servizio di prevenzione e protezione" (Individualisation of the minimum content for the instruction of workers and representatives of ocuppational health and safety).

- **Decreto Ministeriale del 10/03/1998** (G.U. del 07/04/1982 n. 98): " Criteri generali di sicurezza anticendio e per la gestione dell'emergenza nei luoghi di lavoro" (General criteria of fire prevention and emergency management in the place of work).

- **Decreto Ministeriale del 08/09/1999** (G.U. del 22/09/1999 n. 223): "Modificazioni al Decreto Ministeriale del 10/03/1998" (Modification to the norm DM 10/03/1998).

- **Circolare del Ministero dell'interno del 01/03/2002 n. 04** (G.U. del 06/06/2002 n. 131): "Linee guida per la valutazione della sicurezza antincendio nei luoghi di lavoro dove siano presenti persone disabili" (Guide for the evaluation of fire prevention in the place of work of persons with disabilities).

General Regulations of Fire Prevention and Protection

- **Legge dello Stato del 27/12/1941 n. 1570**: "Nuove norme per l'organizzazione dei servici antincendi" (New norm related to the organization of fire protection services).

- **Decreto Pres. Repubblica del 27/04/1955**: "Norme generali e speciali in materia di prevenzione" (General and especial norms related to prevention).

- **Circolare del 05/02/1960 n. 2552/4122**: " Ministero dell'interno – Esami di progetti da parte dei vigili del fuoco" (Evaluation of construction projects made by the fire brigade).

- **Circolare Ministeriale del'interno del 14/09/1961 n. 91**: "Norme di sicurezza per la protezione contro il fuoco dei fabbricati a struttura in acciaio destinati ad uso civile" (Safety norms for fire protection for the manufacture of steel structures employed to civil use).

- **Decreto Ministeriale del 30/11/1983** (G.U. del 12/12/1983 n. 339): "Termini e definitioni ge-nerali e simboli grafici di prevenzione incendi" (General terms and definitions and symbology regarding to fire prevention).

- **Decreto Ministeriale del 26/06/1984**: "Classificazione di reazione al fuoco ed omologazione dei materiali ai fini della prevenzione incendi" (Classification and acreditation of materials used for fire prevention due to its reaction to the fire).

- **Decreto Ministeriale del 06/03/1986** (G.U. del 13/03/1986 n. 60): "Ministero dell'interno – Calcolo dei carico di incendio per locali aventi strutture portanti in legno" (Calculation of fire loads for buildings containing wood structures).

- **Lettera Circolare del 23/01/1987 n. 1169/4101**: "Ministero dell'interno – art. 3 del D.L. 8-3-1985. Carico d'incendio. Legge 818/84" (Article referred to fire load).

- **Lettera Circolare del 07/12/1995 n. P2244/4101**: "Ministero dell'interno – Servizio di prevenzioni incendi – Esame di progetti" (Fire prevention services – Evaluation of construction projects).

- **Decreto Legislativo del 14/08/1996 n. 493** (G.U. del 23/09/1996 n. 223, supplemento ordinario e G.U. del 10/06/2000 n. 134): "Attuazione della direttiva 92/58/CEE concernente le prescrizioni minime per la segnaletica di sicurezza e/o di salute sul luogo di lavoro" (Minimal prescriptions related to safety symbology and/or occupational health).

- **Decreto Ministeriale del 10/03/1998** (G.U. del 07/04/1998 n. 81): "I criteri generali di sicurezza antincendio e per la gestione delle emergenze nei luoghi di lavoro" (General fire protection criteria and emergency management in the place of work).

Fire Prevention and Protection Regulations Specific to Historic Buildings

- **Legge n. 1089 del 01/06/1939** (G.U. del 08/08/1939 n.184): "Tutela delle cose di interesse artistico o storico" (Protection of pieces with artistic or historic importance).
- **Legge dello Stato del 27/05/1975 n. 176**: "Prevenzione antifurto e antincendio delle opere d'arte" (Thievery and fire protection of works of art).
- **Lettera Circolare del 24/09/1985 n. 19917/4161**: "Ministero dell'interno – Prevenzione incendi negli archivi. Interpretazione norme esistenti" (Fire prevention in archives. Explanation of existent norms).
- **Decreto Ministerial del 20/05/1992 n. 569** (G.U. del 04/03/1992 n. 52): "Regolamento concernente norme di sicurezza antincendio per gli edifici storici e artistici destinati a musei, gallerie, esposizioni e mostre" (Regulations specific to fire prevention for historic and artistic buildings destinated to museums, galleries, expositions and samples).
- **Decreto Pres. Repubblica del 30/06/1995 n. 418**: "Regolamento concernente norme di sicurezza antincendio per gli edifici di interesse storico-artistico destinati a biblioteche ed archivi" (Regulations specific to fire prevention for historic and artistic buildings destinated to libraries and archives).

Fire Prevention Certifications

- **Circolare del 01/07/1949 n. 85**: "Certificato di prevenzione incendi" (Certification of fire prevention).
- **Circolare del 23/09(1967 n. 97**: "Ministero dell'interno – Rilascio dei certificati di preventione incendi" (Delivery of the certification of fire prevention).
- **Circolare del 21/11/1984 n. 39**: " Certificazione sulla classificazione di reazione al fuoco dei materiali. Unito a Decreto Ministeriale del 26/06/1984"

(Certification of the classification concerning to fire reaction of materials. Together with the norm DM 26/06/1984).

- **Lettera Circolare del 12/06/1993 n. 9734/4101**: “Certificazioni resitenza al fuoco” (Certification of fire resistance).

- **Decreto Pres. Repubblica del 12/01/1998 n. 37** (G.U. del 10/03/1998 n. 37): “Regolamento recante la disciplina dei procedimenti relativi alla prevenzione incendi” (Regulations regarding to fire prevention procedures).

- **Decreto Ministeriale del 04/05/1998** (G.U. del 07/05/1998 n. 104): “Disposizioni relative alle modalità di presentazione ed al contenuto delle domande per l’avvio dei procedimenti di prevenzione incendi nonché sull’uniformità dei connessi servizi resi dai comandi provinciali dei vigili del fuoco” (General dispositions for the content of fire prevention questionaire and its homogeneity with the services provided by the local fire brigades).

6.1.2 Example of Historic Building: The Uffizi Gallery

Figure 6.1: Main corridor of the Uffizi Gallery.

Brief History and some Background. The Uffizi Gallery (*Galleria degli Uffizi*, in Italian) is one of the oldest museums in Europe and most representative in the world. The gallery is housed in the Uffizi’s Palace (*Palazzo degli Uffizi*), which is located in the city of Florence (Tuscany Region), Italy. The palace construction begun in 1560 by Giorgio Vasari under the command of Cosimo I de’ Medici. And finished in 1581 with the contributions of Alfonso Parigi and Bernardo Buontalenti by introducing the Tribuna degli Uffizi and the Teatro Mediceo at the inside of the Palazzo. Although in actual days the Uffizi is a permanent gallery, the original purpose of the building was to allocate the new offices (or *uffizi* in Italian) of thirteen

Florentine magistrates, together with the tribunal and the state archive [8]. The usage of the Uffizi's Palace as a Gallery started around the year 1581 with Francesco I (Cosimo I 's child), who disposed several paintings, sculptures and priced objects of the Medici's family in the last floor of the building. Over the years, the collection expanded continuously into further parts of the palace [74, 75].

Just shortly before the extinction of Medici's dynasty (eighteenth century) Anna Maria Luisa, the last Medici heiress, donate the complete art collection of the family to the city of Florence [75]. From that time on, the gallery was open to visitors by request, and in 1769 it was officially opened to the public as a museum [179].

Thus, the distinctive attraction of the Uffizi Gallery, in comparison to other museums, obeys not only to its beauty and architectural value, but also due to the content and richness of its exposition and artists, which since the early beginning of the gallery is in continuous expansion. Some of its most representative artists are Sandro Botticelli (*Primavera*, *The Birth of Venus*), Leonardo da Vinci (*The Annunciation*), Caravaggio (*Bacchus* and *Medusa*) among many others. The actual gallery has an exhibition space of circa $17000\,m^2$ (in 2006) and is distributed over three floors [187]. A library and several lecture rooms are located in the first floor. Meanwhile, the second floor allocates the 43 exhibition rooms and a restaurant with a terrace. The ground floor is destinate for general public services like a bookshop, information, wardrobe and check-in. Future expansions to the actual surface are in project, which considers an increment to almost fifty percent, additional to the actual surface $(\text{circa}\,26000\,m^2)$, by the end of the project [187].

6.1.3 Demographic Characteristics of the Visitors

The Uffizi Gallery is one of the most visited museums in Italy, with a rate over a million visitors per year. For instance, in 2008 the gallery was situated in the third place of a ranking of the thirty most toured Italian museums [3]. Regarding to evacuation dynamics, a realistic simulation of a building evacuation depends not only on the total amount of visitors but also on their individual characteristics. A first step in the definition of the demographic characteristics of the visitors of the Uffizi Gallery is given in Table 6.1. This table presents the number of yearly visitors to the Uffizi Gallery from the period of 1996 to 2009, together with the percentage of paid (with or without cost reduction) and free admission tickets. The assignation of the different types of tickets corresponds to specific criteria given by the Gallery [179]. This classification will help in the definition of the demographic characteristics of the visitors and their possible distribution within a day.

Year	Total of visitors	Percentage paid ticket	Percentage free ticket	Averaged visitors per opened day
1996	1’166,173	82.8	17.2	3,762
1997	1’332,349	80.3	19.7	4,298
1998	1’495,498	81.5	18.5	4,824
1999	1’419,534	81.8	18.2	4,579
2000	1’414,484	83.5	16.5	4,563
2001	1’489,024	83.7	16.3	4,803
2002	1’489,452	82.5	17.5	4,805
2003	1’495,623	79.8	20.2	4,825
2004	1’429,546	81.4	18.6	4,611
2005	1’342,558	82.3	17.7	4,331
2006	1’664,232	81.0	19.0	5,368
2007	1’615,986	79.0	21.0	5,213
2008	1’554,256	80.2	19.8	5,014
2009	1’530,346	78.3	21.7	4,937

Table 6.1: Number of visitors to the Uffizi Gallery per year (period 1996-2009). Statistical data obtained from [126]. The averaged number of visitors per day was calculated considering 310 opening days per year.

In general, the Uffizi Gallery distinguishes three types of admission tickets: reduced, free and the normal ticket. Reduced and free tickets are subjected to several restrictions [179]. Thus, in accordance to the regulations of the gallery, tickets with a *reduction* in price are addressed to the following persons:

- Students of the European Union between 18 - 25 years old.
- Full or part-time teachers of Italian schools.

On the other hand, *free tickets* are given to persons who fulfil the following criteria:

- Citizens of the European Union under the age of eighteen or over the age of sixty five and visitors under the age of twelve must be accompanied.
- Groups and parties of students from state and private schools in Italy and the European Union, accompanied by their teachers (subject to booking).
- Teachers and students enrolled in specific faculties or corresponding institutes within the European Union.

- Tour guides from the European Union in the exercise of their professional activities. In the same way, tourist interpreters from the European Union when their assistance is required alongside the guide.

- Citizens of the European Union with disabilities and a family member or other accompanying person.

- Voluntary workers performing activities for the promotion and enhancement of knowledge of the cultural heritage, on the basis of agreements drawn up with the Ministry pursuant to article 112, subsection 8, of the Code “Attività di promozione e diffusione della conoscenza dei beni culturali”.

- For reasons of study or research, certified by schools or universities, academies and research and cultural institutes in Italy and abroad, and by the Ministry for the Cultural Heritage and Activities, or for specific motivated requirements.

- And employees of the Ministry for the Cultural Heritage and Activities as well as members of ICOM (International Council of Museums).

Finally, the *normal ticket* is open to the rest. However, this category commonly corresponds to tourists in general without distinctions of age or type (i.e., single, couples, small or big families, and organised visits).

Table 6.2 summarises the demographic characterisation of the yearly visitors of the Uffizi in accordance to the type of admission ticket that they present. For a realistic simulation of the evacuation of the gallery, the demographic characterisation and distribution of the visitors within a representative visiting-day are required. For this purpose, a proposed daily characterisation of the visitors is based on distribution proposed in [8]. The proposed distribution is based on the number of visitors to the Uffizi Gallery corresponding to the year 2005, with regards to the different types of tickets sold in the complete period.

The corresponding results are shown in Table 6.3. A similar trend among the yearly distribution of the tickets for the period 1996-2009 and the specific for the year 2005 is found (Tables 6.1 and 6.2, respectively). Therefore, we assume that the distribution of tickets is constant over the years for the period of 1996 to 2009. However, in those occasions when the Gallery is opened with no cost of admission, the percentage of occupancy of free tickets may increase up to hundred percent [8]. This situation is not considered in this study.

Ticket type	Age (years old)	Occupation	Handicap / Disabilities	Objective of the visit	Type of visitor
Reduced	18-25	Students	Not mentioned	Study or visit	Single or in groups
	Not mentioned	Teachers	Not mentioned	Study or visit	Single or in groups
Free	Under 18	Not mentioned	Not mentioned	Visit	Under 12 years old must be accompanied
	Over 60	Not mentioned	Not mentioned but possible	Visit	In groups
	Not mentioned	Students	Not mentioned	Study	In groups
	Not mentioned	Tour guides	Without	Guide	In big groups
	Not mentioned	Companion	Without	Accompany	With handicapped companion
	Not mentioned	Any	With	Visit	With companion
	Not mentioned	Volunteers, personnel of Ministry and ICOM	Not	Visit	Single or in groups
Normal	Any	Tourist or any	Without	Visit or tour	Single or in groups

Table 6.2: General characterisation of the visitors of the Uffizi Gallery, based on the current regulations applicable to the admission in the gallery [179].

Ticket type	Percentage of occupancy
Reduced	From 2 to 5 %
Free	From 5 to 16 %
Normal	From 7 to 88 %

Table 6.3: Daily distribution of visitors based on the ticket type, as suggested in [8] (page 128).

6.2 Vulnerability of Evacuating Crowds in Historic Buildings: Definition of Variables

Nowadays, safety in historic buildings continues to be an open problem. In particular, due to the increasing number of regulations and their extended application in modern buildings (with possible overlapping specifications) which in many cases contradict the criteria and standards established for the protection of historical goods [155]. An example of this situation are the general criteria for fire prevention given in the Italian norm DM 10/03/1998 ("General criteria of fire prevention and emergency management in the place of work") and the particular specifications prescribed by the Italian Ministry of Cultural Goods (Ministero dei Beni Culturali) in the norm DM 20/05/1992 n. 569 ("Regulations specific to fire prevention for historic and artistic buildings used as museums, galleries, expositions and samples"). In general terms, historic buildings present additional characteristics which make them distinctive from modern buildings, and therefore shall be considered in order to guarantee the desired level of safety within the occupants and the building itself. Although the architectonic variety of historic buildings worldwide is bigh, most of their characteristics keep similarities. Examples of these are summarised as follows:

1. Historic buildings and their content (artistic and historic goods) are *not reproducible*. Thus, they have equal level of relevance as for the occupants (or visitors) of the building. This is, the level thievery protection of the goods as well as the conservation of the heritage (i.e., works of art or even the building) should not affect or decrease the level of protection and safety of the occupants of the building, and in the other way around.

2. However, the high *heterogeneity* between the broad amount of types and construction epochs of historic buildings, their construction materials and technology, limit the use of standard measures for fire prevention and protection norms, commonly applied to modern buildings.

3. Moreover, historic buildings are commonly categorised as *highly vulnerable* [7, 8, 155]. In special, due to the following cases:

    (a) The lack of knowledge of the structural behaviour of the building when fires or natural catastrophes (i.e., earthquakes, floods) occurs,

    (b) the construction materials (e.g. wood structures) may increase the fire loads of the building,

    (c) the existence of highly valued artistic and historic goods at the inside of the building (like the case of galleries, museums and archives or libraries), and

    (d) the lack of modernisation and adaptation to modern norms and standards for fire prevention, protection and emergency assistance.

In the context of evacuation dynamics, many aspects of particular events which may induce to a successful building evacuation (i.e., alarming, recognition and pre-movement times) have been discussed for the calculation of *"engineering-based"* evacuation times together with more reliable estimations (ASET and RSET, in Section 2.1.2 page 13). However, and as discussed in Section 3.1.2, further situations inherent to pedestrian dynamics like *self-organisation* and their corresponding *motion patterns* influence the diverse interactions among the evacuating crowd and their behaviour (see examples in Section 5.1.3). And therefore shall be studied and considered in novel models of evacuation dynamics.

A further aspect of safety in the built environment implies the estimation and the posterior reduction of risk. In Section 2.2.2 *risk of fatal events* was defined as a direct function of the sources of hazards (natural or man-made), the vulnerability and exposure of the occupants (or visitors) of the building (Equation 2.2). As a first approach in the evaluation of risk due to evacuations, the present study focuses on the study of vulnerability of the occupants.

The term *vulnerability* in the built environment is referred as the susceptibility of the occupants to be involved in an accident and/or to be injured. In accordance to Sime [221], vulnerability depends on three main factors: the characteristics of the individuals (visitors), the characteristics of the environment (building) and the actions (or behavioural responses) taken by the individuals. Thus, without much mathematical rigour vulnerability of the occupants when pursuing an evacuation is expressed as:

$$V(t) = f(C_N, s(t), C_c) \tag{6.1}$$

where $V(t)$ is the estimated vulnerability of the occupants of the case-study building at any time, C_N and C_c are the characteristics of the N-individuals of the evacuating crowd and the characteristics of the case-study building (c) respectively. Finally $s(t)$ is the state of the system (Equation 5.13), which contains the behavioural responses (actions) taken by the individuals of the evacuating crowd at any time. A generalisation of the vulnerability may suggest C_N and C_c to be random variables. However, the present work focuses on the study of a particular case-building and therefore both variables are taken as given.

6.2.1 Characteristics of the Uffizi Gallery

This section presents general characteristics of the Uffizi Gallery. Of special interest is the distribution of works of art and their specific allocation among the exhibition rooms. Due to the fact that the visitors present particular interest to specific works of art, the exhibition rooms which contain this works present higher amount of visitors than others. For instance, the exhibition rooms 10 to 15 in the second floor of the gallery. Beside the works of art, the gallery allocate further non-permanent exhibitions and offices for administrative purposes, which are not open to the public in general, and therefore are not considered in this study. In this sense, the simulation of the evacuation of the Uffizi Gallery is done for specific case-study scenarios. The Uffizi Gallery is located inside a three floor building (ground-, first-, and second-floor). Part of these rooms are open to the public. Figures 6.2, 6.3 and 6.4 present those exhibition rooms and services available for the public. The selected case-study scenarios are described as follows.

Ground Floor

In general terms, the main entrances and exits of the building together with general public services like cloakroom, counters for audio-guides, post office, information desk and reservations are allocated in the ground floor of the building. The access to the gallery is restricted (i.e., forbidden objects or substances). Thus, there is a check point at each entrance. However, new visitors may come into the building at a rate of 15 minutes [8, 179]. The access to the gallery is done through two independent entrances: one for visitors with a reservation and another for visitors without one.

Figure 6.2 presents the general distribution of the main entrances, exits and public services allocated in the ground floor. Each room is identified by means of a legend. The notation together with the corresponding explanation is given in Table 6.4. Those areas which are open to the public have been marked in red.

In the context of evacuation dynamics, exits and entrances to the building have a central role for a successful evacuation. Beside the main entrances and exits to the building, the ground floor of the Uffizi Gallery allocates further public services. This situation may limit in certain way a fluent evacuation of the building. Thus, simulations of the evacuation of the ground floor of the gallery are performed. Numerical results of these simulations are shown in Section 6.3.2.

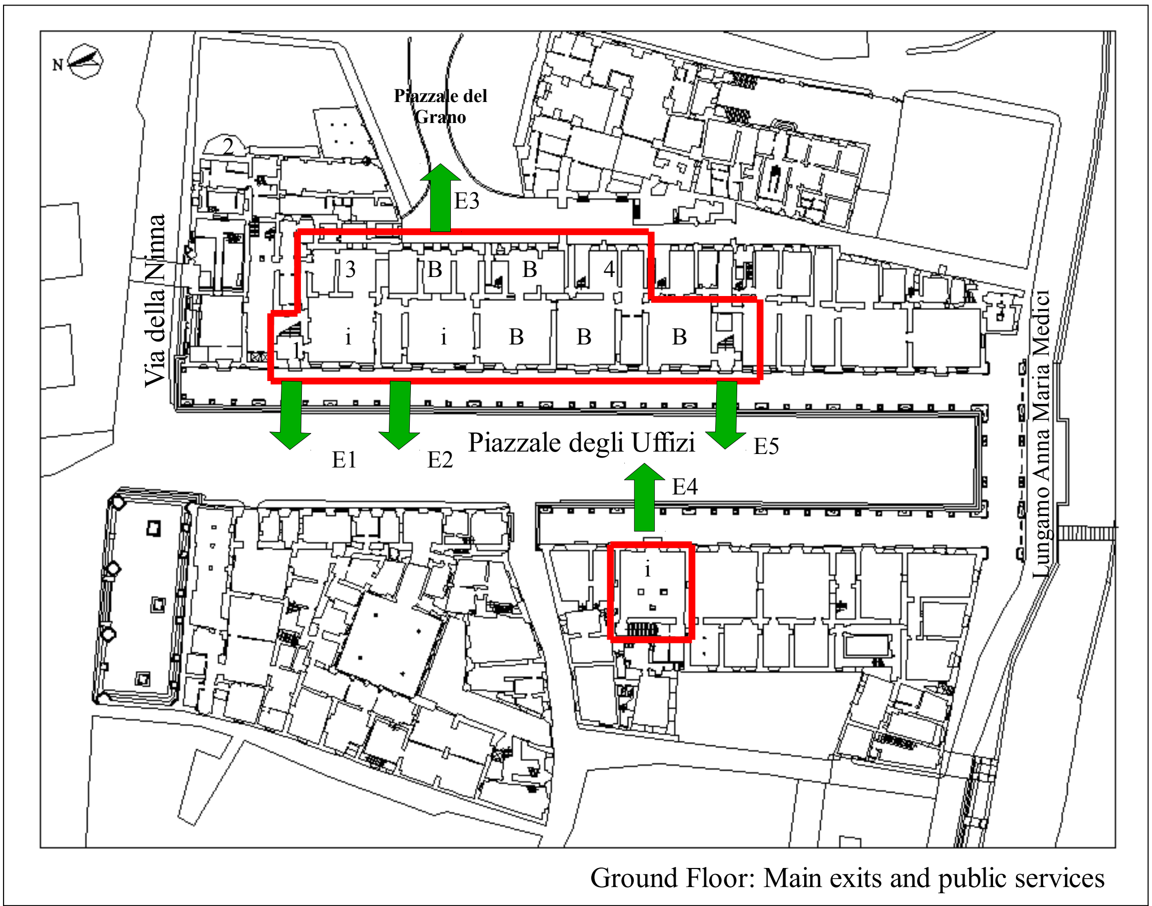

Figure 6.2: View of the ground floor of the general state of the Uffizi Gallery in the year 2005 [8, 74].

Legend	Explanation	Legend	Explanation
1	Aula San Pier Scheraggio	B	Bookshop
2	Vasarian stairs	E1	Entrance for visitors with reservation
3	Cloakroom and audio-guides	E2	Entrance for visitors without reservation
4	Post office	E3	General exit of the gallery
i	Information desk and reservations	E4-E5	Alternative exits of the gallery

Table 6.4: Distribution of exhibition rooms and public services located in the ground floor of the gallery.

First Floor

In opposition to the second floor of the gallery, temporal exhibitions are allocated in the first floor. Thus, this floor presents a restricted number of visitors. In this sense, the evacuation of this area shall not introduce an impact over the evacuation of the complete building. Therefore, the simulation of temporal exhibition rooms has been left for future works. Figure 6.3 presents the distribution of the exhibition rooms allocated in the first floor of the gallery (in red colour), together with the staircases (in green colour).

Legend	Explanation	Legend	Explanation
1	Hall and staircase	5-9	Caravaggio and Caravaggesque painters
2-3	Prints and drawings, exhibition and lecture rooms	A	Temporary exhibitions
4	Library	B	Bookshop

Table 6.5: Distribution of exhibition rooms and public services located in the first floor of the gallery.

Table 6.5 presents legends and a short explanation of the different rooms and public services distributed in the first floor of the gallery. In the context of evacuation dynamics, fluent circulation through staircases within an evacuation is commonly desired. However, stagnations in lower floors may take place with high amounts of individuals, influencing in this way the evolution and dynamics of the evacuation. Numerical results are given on Section 6.3.2.

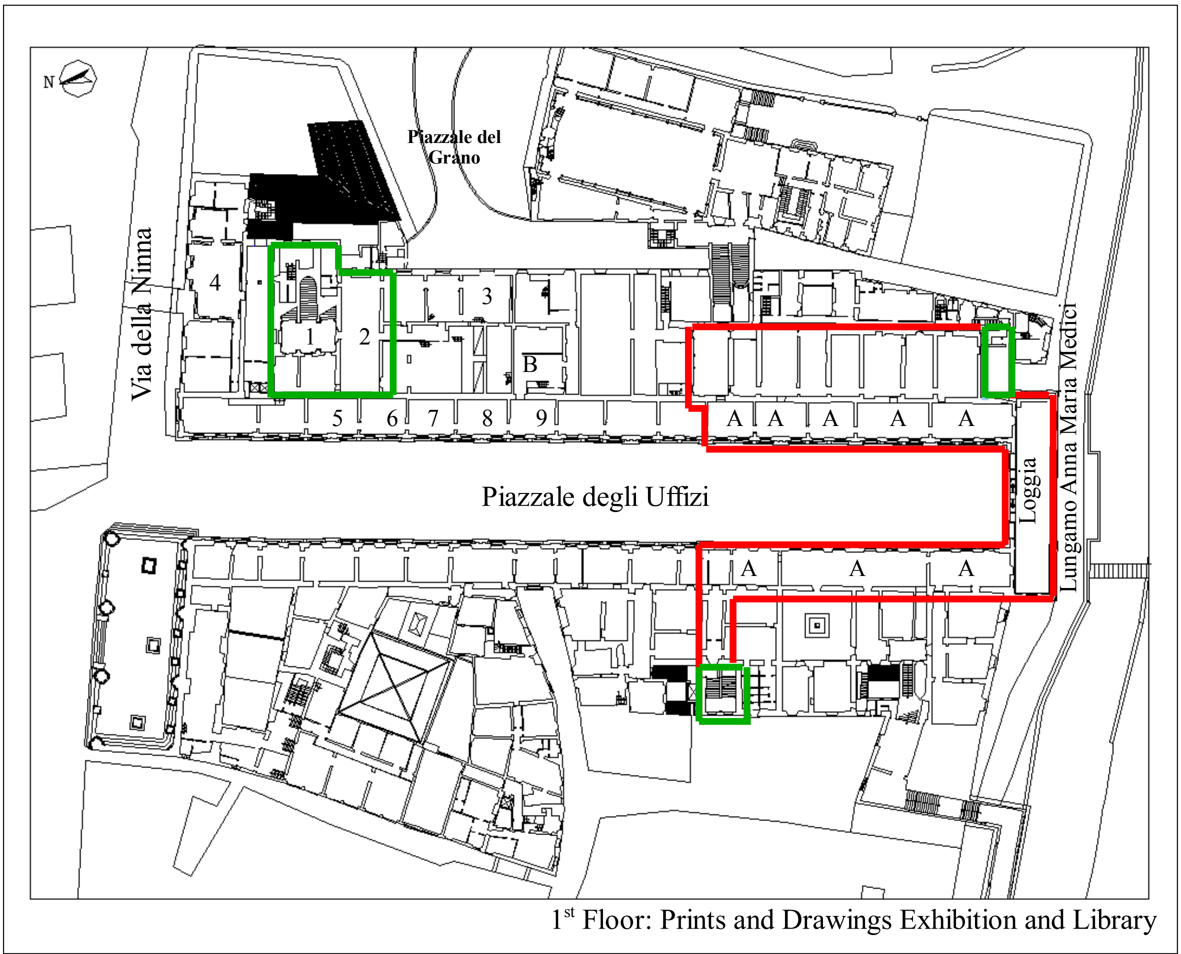

Figure 6.3: View of the first floor of the general state of the Uffizi Gallery in the year 2005 [8, 74].

Second Floor

The main and permanent exhibitions of the gallery are allocated in the second floor of the building. Thus, high concentration of visitors is here characteristic and therefore relevant for the study of evacuation dynamics.

Figure 6.4 presents the distribution of the exhibition rooms which are commonly accessible for the public in general (in red colour) and the corresponding staircases (in green colour). Meanwhile, Table 6.6 presents legends and a short explanation of the different rooms and public services found in this floor. Due to its relevance within the evacuation process of the gallery, simulations have been performed. In this sense, numerical results of these simulations are shown in Sections 6.3.1 and 6.3.3.

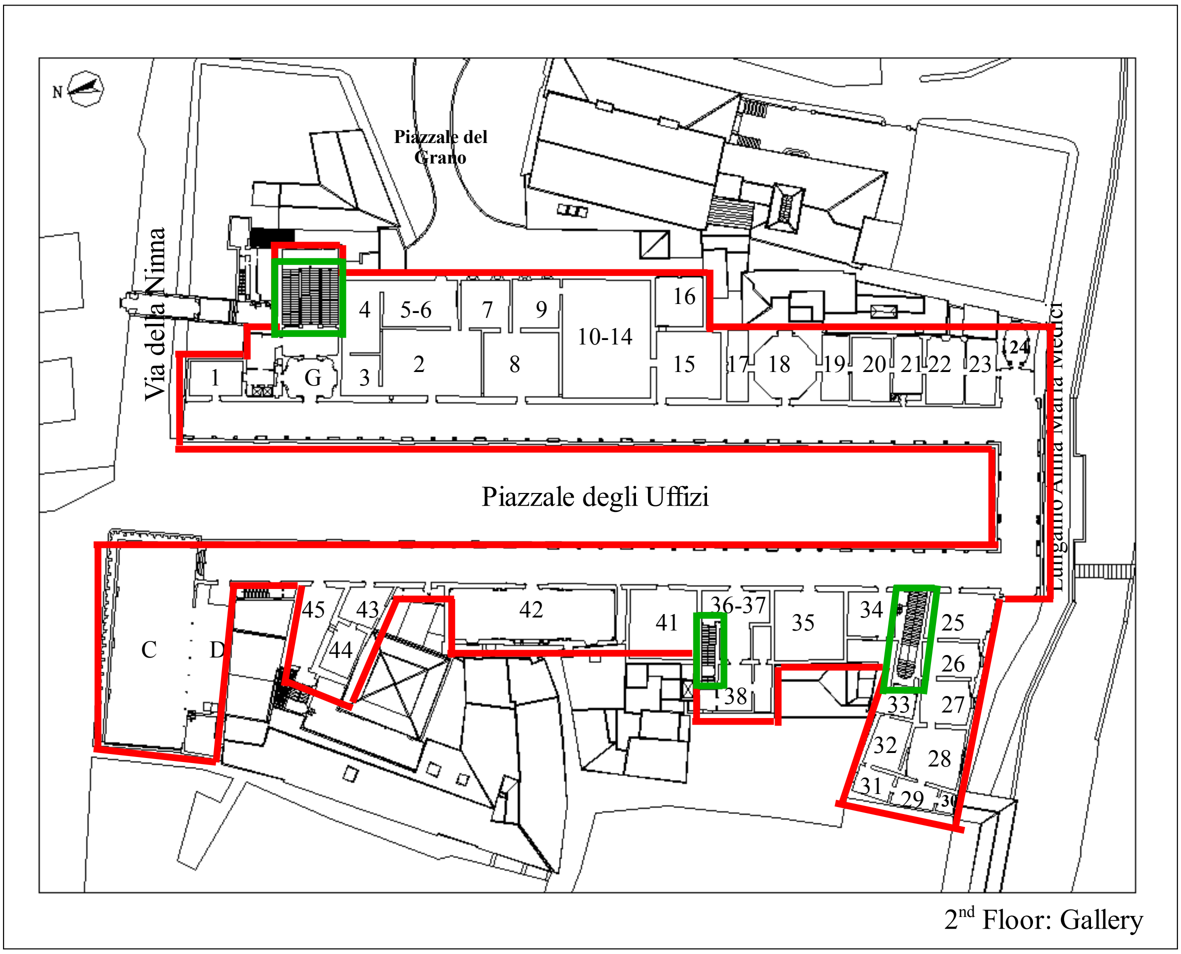

Figure 6.4: View of the second floor of the general state of the Uffizi Gallery in the year 2005 [8, 74].

6.2.2 Characteristics of the Visitors of the Uffizi Gallery

Another influencing factor of evacuation dynamics are the physiological characteristics of the visitors. In particular due to their body-dimensions and maximum walking speed. In Section 6.1.3 a generalised classification and distribution of the demographic characteristics of the visitors was performed. According to Tables 6.1 and 6.2, the demographic characteristics of the visitors can be categorised into two main classes: (i) young and healthy individuals, and (ii) old individuals or individuals with a limited discapacity.

Regarding to the study of vulnerability in the built environment, these demographic differences of the visitors shall be considered. In particular to their physiological characteristics (for instance, an averaged body width of the visitors) and the maximal walking speed possible according to their age. Based on these criteria, Table 6.7 presents a simplified classification of the common visitors of the gallery or *person types*.

Legend	Explanation	Legend	Explanation
1	Classical antiquity	26	Raphael and Andrea del Sarto
2	Tuscan school of the 13*th* c. and Giotto	27	Pontormo and Rosso Fiorentino
3	Sienese school of the 14*th* c.	28	Titian and Sebastiano del Piombo
4	Florentine school of the 14*th* c.	29	Dosso and Parmigianino
5-6	International Gothic	30	16*th* c. Emilian paintings
7	Early Renaissance	31	Veronese
8	Lippi	32	Bassano and Tintoretto
9	Pollaiolo	33	Corridor with 16*th* c. paintings
10-14	Botticelli	34	16*th* c. Lombard paintings
15	Leonardo da Vinci	35	Barocci and the Tusca Counter-Reformation painters
16	Maps	36-37	Antiquity hall
17	Mathematics	38	Hermaphrodite
18	The Tribuna	41	Rubens
19	Perugino and Signorelli	42	Niobe
20	Dürer	43	17*th* c. Italian and European painters
21	Giambellino and Giorgione	44	Rembrandt and the Flemish painting of the 17*th* c.
22	Flemish and German Renaissance painters	45	18*th* c. Italian and European painters
23	Mantegna and Correggio	C	Loggia della Signoria terrace
24	Miniatures	D	Belvedere
25	Michelangelo	G	Lorraine hall and ticket check

Table 6.6: Distribution of exhibition rooms and public services located in the second floor of the gallery.

Person type	Averaged body width (m)	Maximal walking speed (m/s)	Explanation
A	0.5	1.4	Averaged individual [242]
B	0.45	1.25	Individuals between 14 and 64 years old [146]
C	0.5	0.97	Individuals older than 65 years [146]

Table 6.7: Classification of the population (of visitors) considered for the simulated evacuation scenarios.

6.3 Numerical Results

This section presents the numerical results of the simulated evacuations, together with their corresponding distribution of evacuation times, individual walking speeds, trajectories and upcoming motion patterns of each test scenario. For the study of vulnerability of the Uffizi Gallery, the present thesis is centred in those areas with high relevance for the evacuation process. In this sense, we select three test scenarios of the gallery. The initial position of pedestrians (within an artificial “drop-zone”) and their initial walking direction are randomly determined. At first the numerical results are briefly present without judgement. The discussion and concluding remarks of the results are given in Section 6.4.

6.3.1 Second Floor: Exhibition Rooms 2 to 15

As an introduction to evacuation dynamics and their influencing factors, the exhibition rooms 2 to 15 of the second floor of the Uffizi Gallery have been selected as our first case study scenario. The selection of this area correspond to the following characteristics which make this exhibition rooms distinguishable from other areas of this floor. First, the nearness to the main staircases (a direct connection to the entrance of the building) makes this area to be the “starting-point” of the touring visit through the gallery. Second, the extended international recognition of the works of arts of Botticelli and Leonardo da Vinci (exhibed in the rooms 10 to 15 of this area), makes this part of the building a common area of interest among visitors. And third, due to the existing interconnections among the exhibition rooms of this area, which is comparable, makes this area to be a good (and small-scaled) representation of the rest of the gallery. For this scenario an amount of 401 visitors are considered and distributed according to [8].

Based on this information, simulations were performed with two different scenarios: (1) all visitors allocated in this area have the same physiological characteristics (averaged body-width and maximal walking speed possible) which corresponds to the characteristics of the averaged individual of type A (defined in Table 6.7). For the scenario (2) fifty percent of the considered visitors are individuals of type B. Meanwhile, the restant fifty percent is of type C (values were previously shown in Table 6.7). Figures 6.5 and 6.6 present the obtained trajectories and motion patterns for both scenarios, without significant differences. Figure 6.7 presents the evacuation time distribution for scenario (2). Significant differences (of around 20 percent) in the total evacuation time

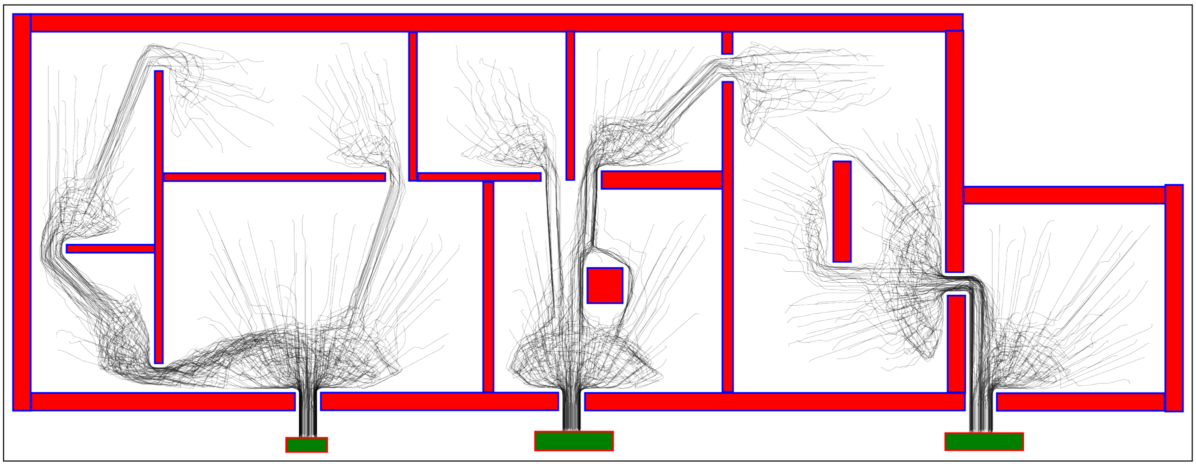

Figure 6.5: Resulting trajectories and motion patterns of test scenario (1). All considered visitors are of type B.

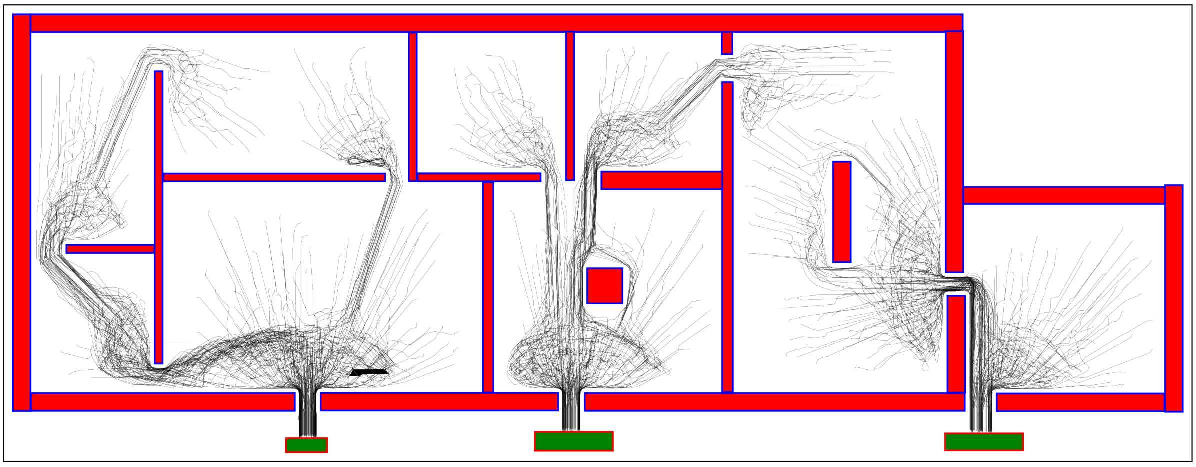

Figure 6.6: Resulting trajectories and motion patterns of test scenario (2). The considered visitors are of type B and C.

were found in both scenarios, as shown in Figure 6.8. Moreover, a strong decay in the walking speed of the individuals is present within the first 20 seconds of the evacuation for both scenarios. The maximum walking speed possible is achieved in the last seconds of the evacuation.

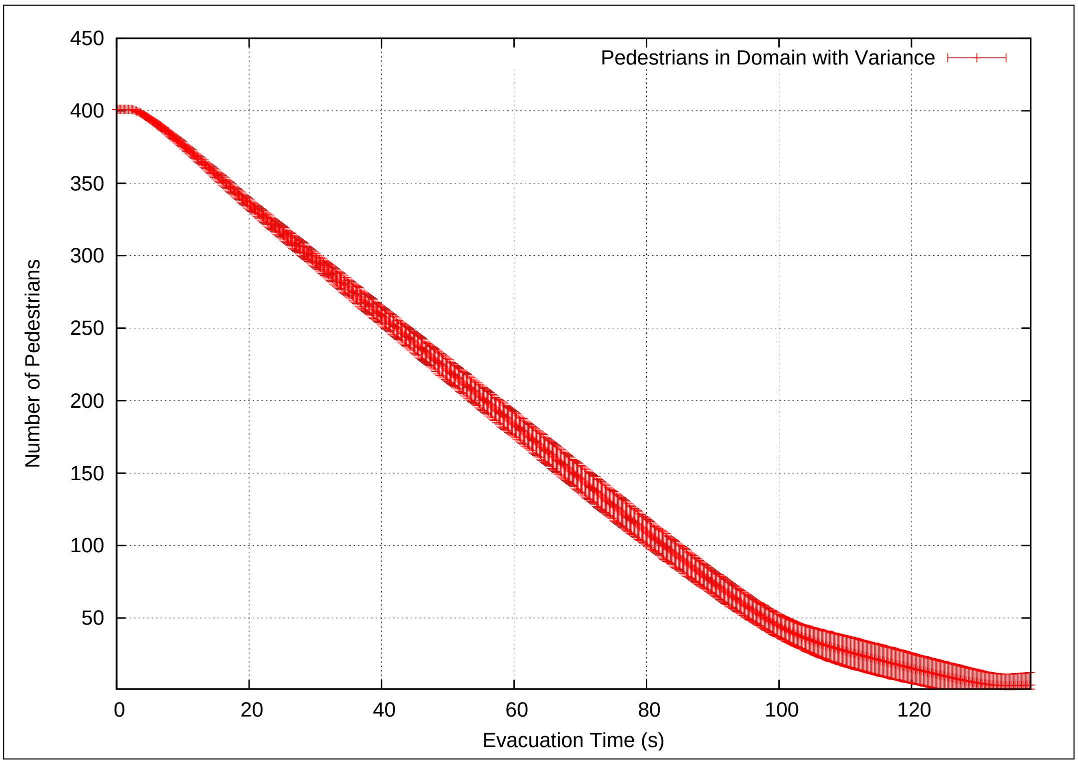

Figure 6.7: Mean values and the variance of evacuation times obtained for test scenario (2), after 983 random realisations.

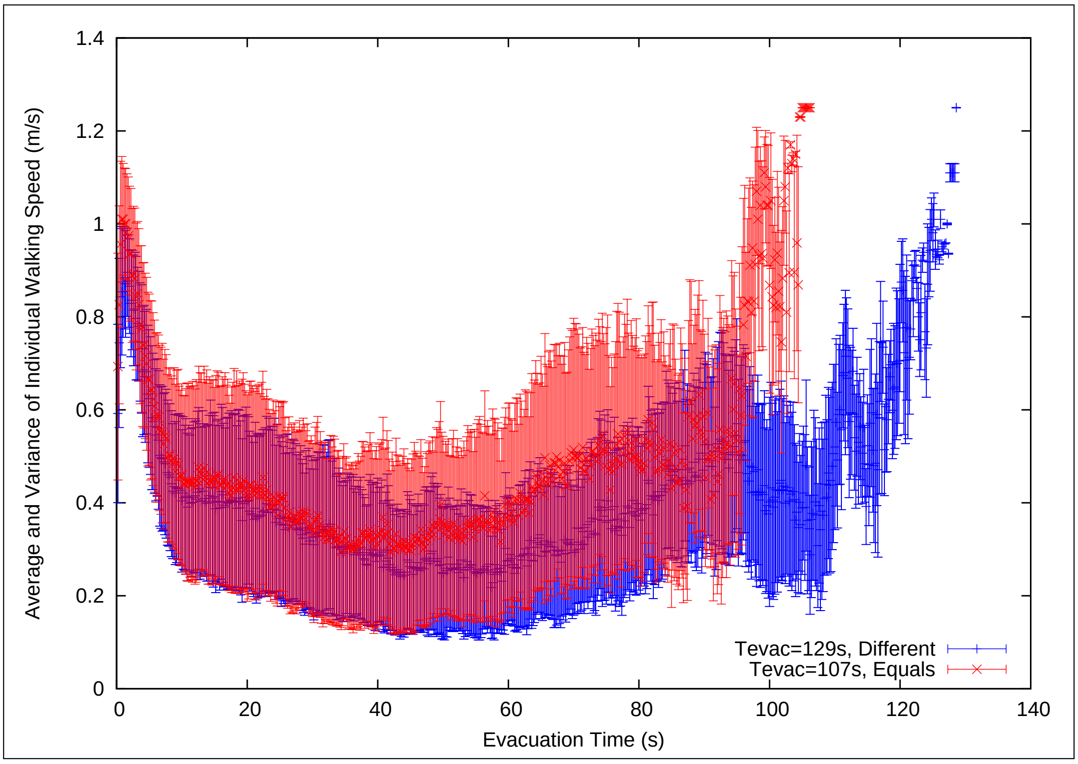

Figure 6.8: Mean values and the variance of individual walking speeds obtained for test scenario (1) and (2), after one trial each.

6.3.2 Main Exits

For the correct simulation of the evacuation of a building, all the accesses (into and out of) the building are relevant. For the particular case of the Uffizi Gallery, the main entrances and exits of the building are allocated in the ground floor (as shown in Figure 6.2). For the analysis of this area, we present two case-studies. A fist one, the scenario (1) which do not considers the egress of visitors located in upper floors (a so-called "static-scenario"). The second case, the scenario (2) do considers the egress of visitors located in upper floors at the moment of the evacuation (a so-called "inflow-scenario").

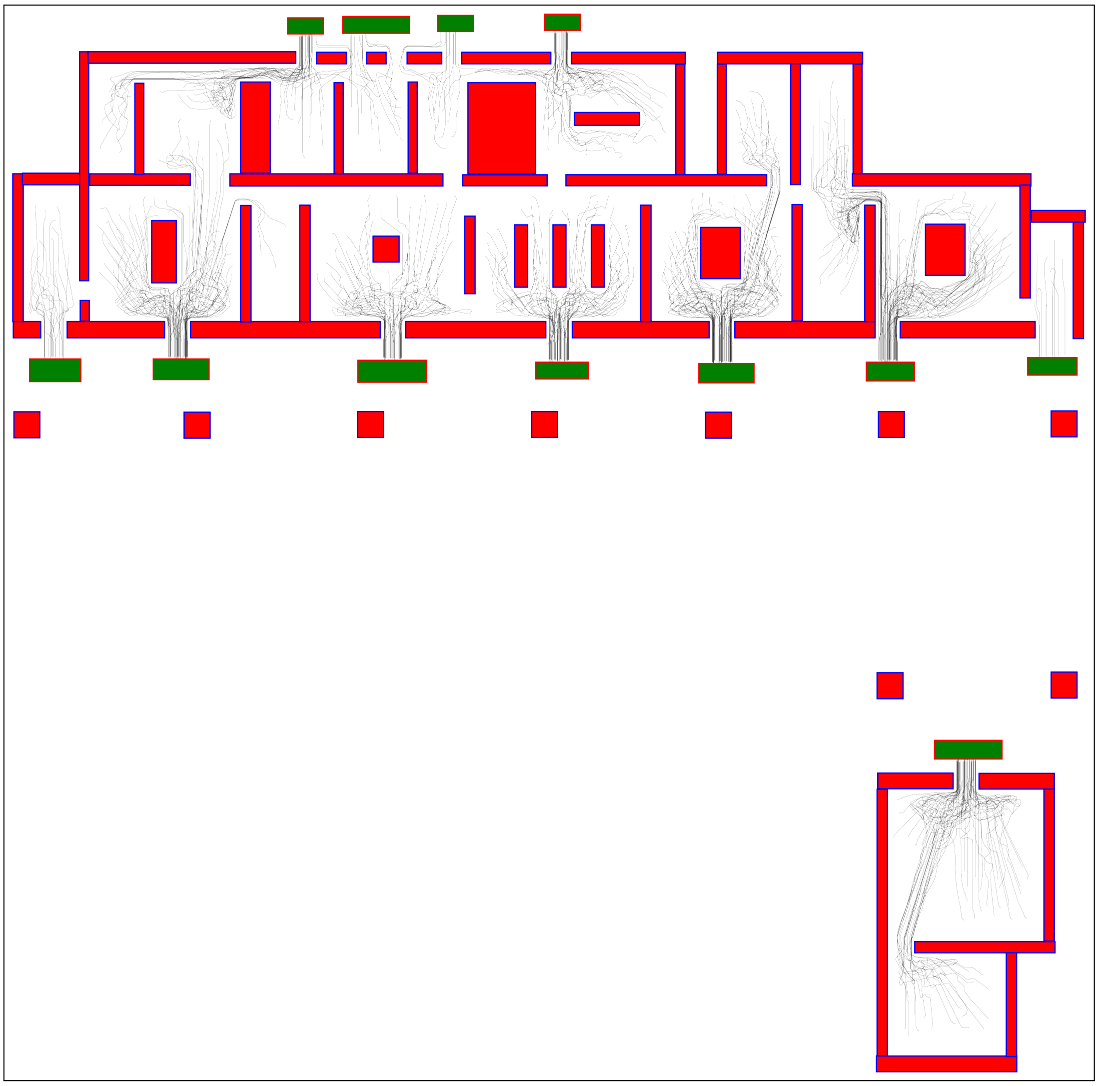

Figure 6.9: Resulting trajectories and motion patterns of test scenario (1).

In accordance to the data provided in [8], in scenario (1) we consider an amount of 467 visitors distributed in the ground floor at the moment of the evacuation. Meanwhile, for scenario (2) additional 1618 visitors of the upper floors of the building are considered (with an inflow rate of 4 individuals per second). For both scenarios, individuals of type B and C were considered.

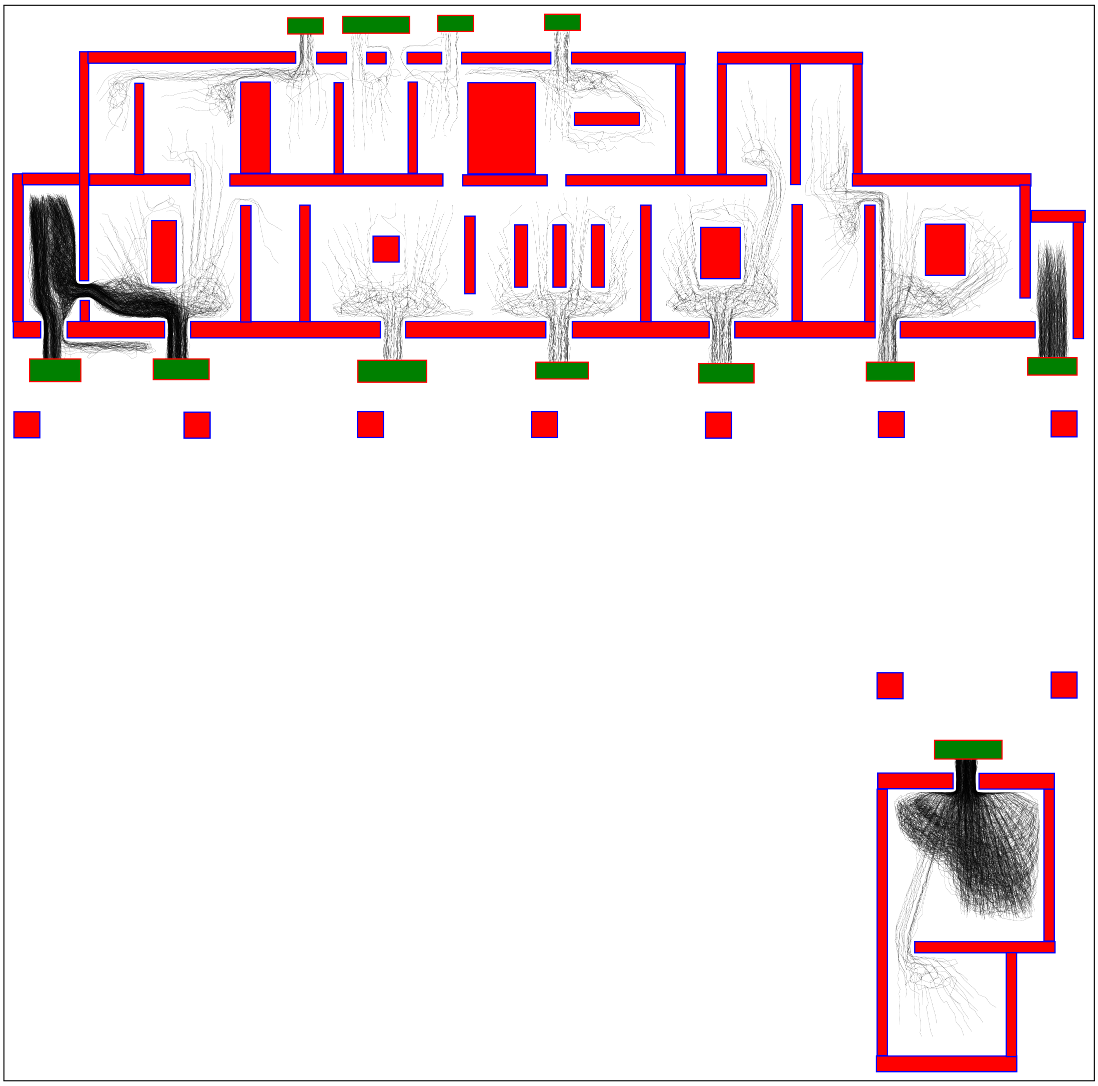

Figure 6.10: Resulting trajectories and motion patterns of test scenario (2).

The trajectories, motion patterns, evacuation times and individual walking speed distributions of scenarios (1) and (2) are shown in Figures 6.9 to 6.14, respectively. Regarding to the trajectories and the upcoming motion patterns, significant differences among both scenarios were not found. However, for the inflow case high evacuation loads are observe in the exits with staircases. Due to the introduction of additional visitors (assumed to come from the upper levels of the building) a significant increase of the evacuation time is observed for scenario (2) in comparison to the evacuation times obtained for the static case. Moreover, significant variances in the walking speed were observed for scenario (2).

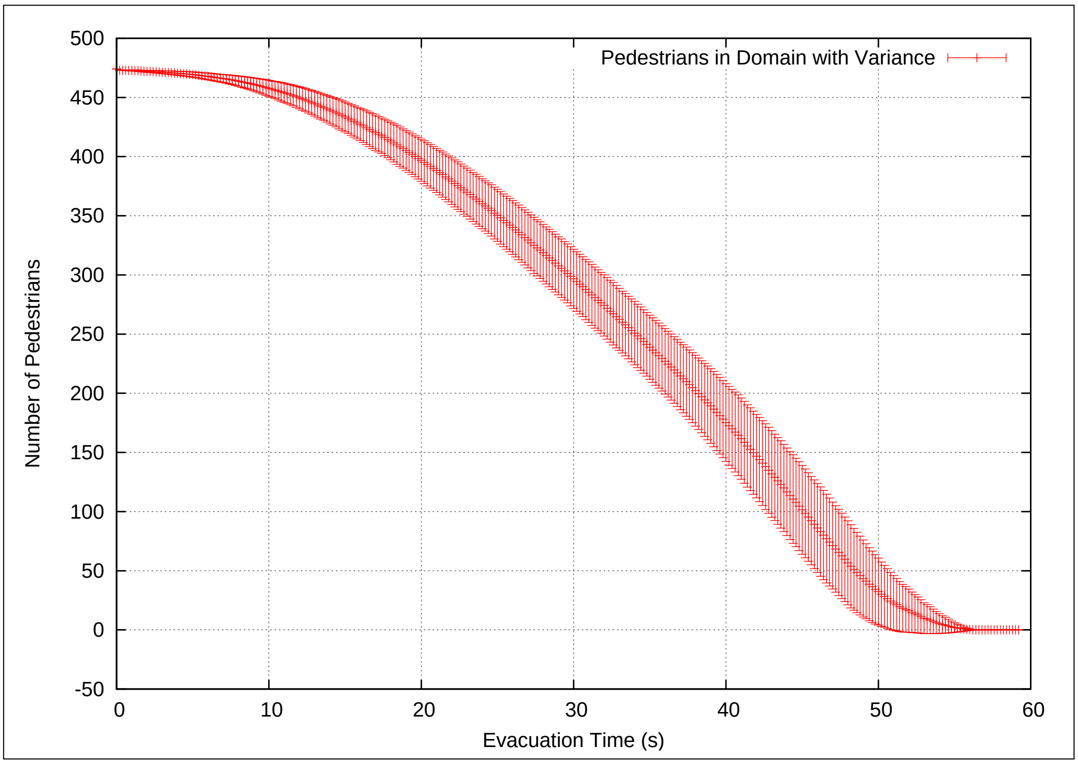

Figure 6.11: Mean values and the variance of evacuation times obtained for test scenario (1), after 244 random realisations.

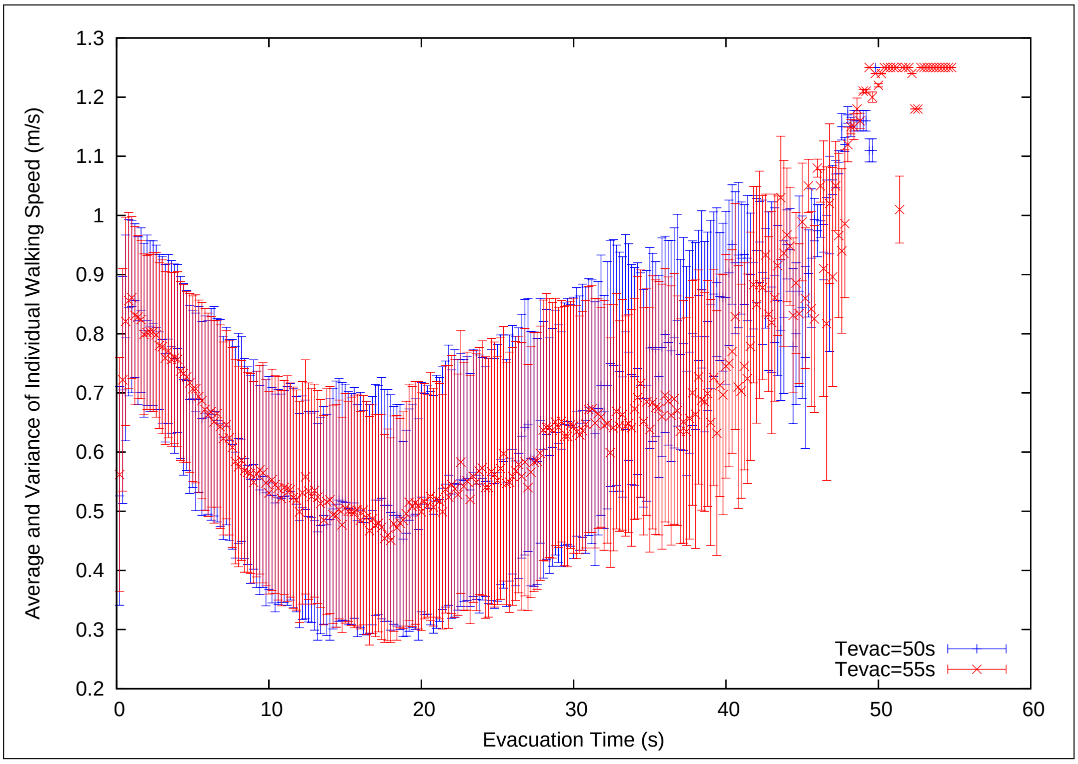

Figure 6.12: Mean values and the variance of individual walking speeds for test scenario (1) considering two trials.

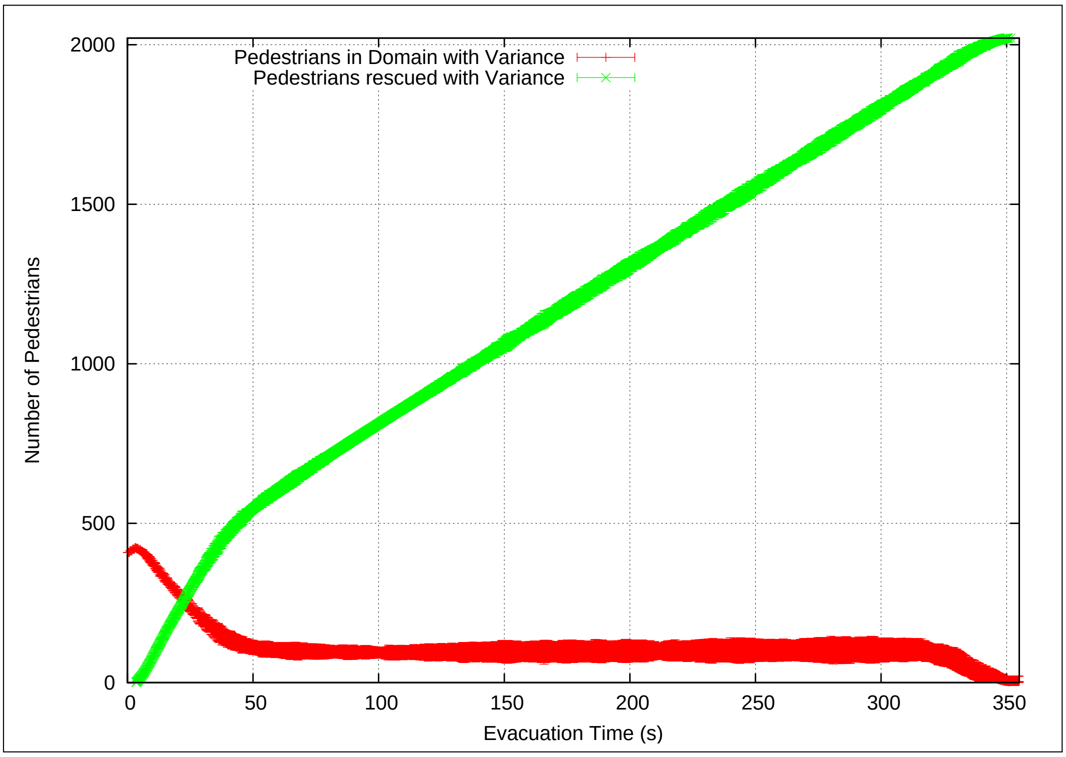

Figure 6.13: Mean values and the variance of evacuation times obtained for test scenario (2) after 31 random realisations. The inflow of individuals from upper levels of the building are represented with colour red.

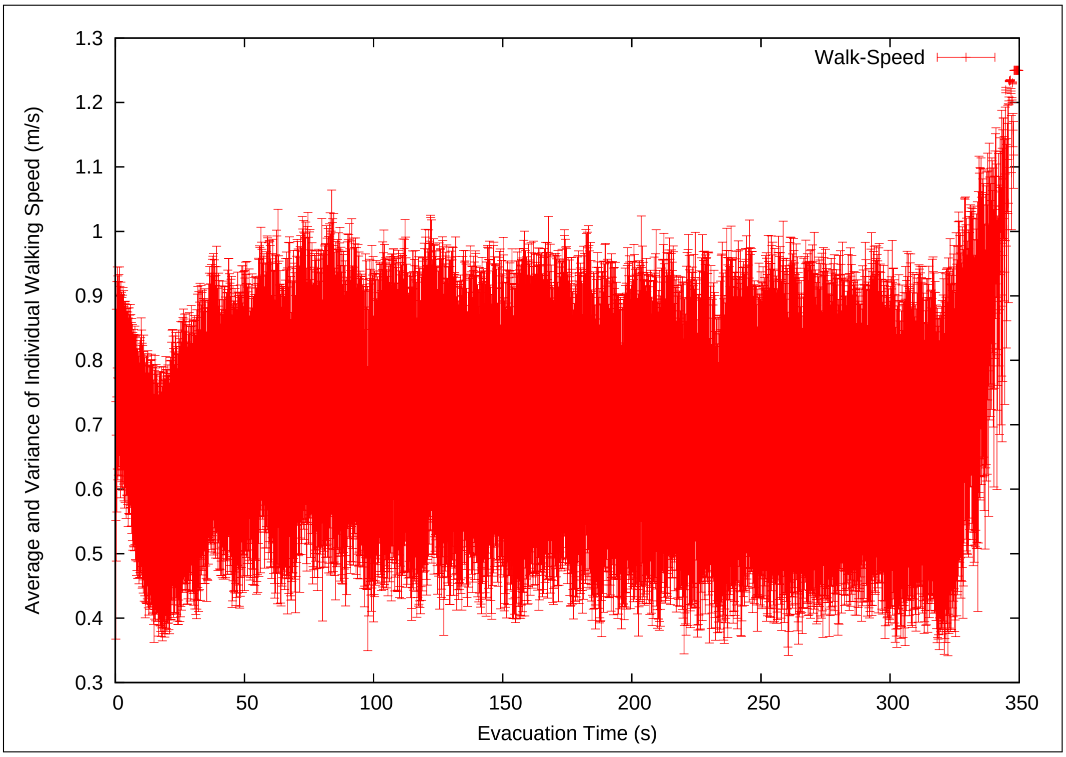

Figure 6.14: Mean values and the variance of individual walking speeds obtained for test scenario (2), after one trial.

6.3.3 Second Floor: Entire Exhibition Area

The study of evacuation dynamics in the Uffizi Gallery is concluded with the simulation of the evacuation of the second floor of the building. For this purpose, two further scenarios are considered. In scenario (1) all visitors allocated in the second floor present the characteristics of the individual type B. Meanwhile, for scenario (2) fifty percent of the visitors are individuals of type B and the other fifty are of type C (see Table 6.7). In both scenarios an amount of 1173 visitors are considered and distributed according to [8].

Figures 6.15 and 6.18 present the obtained trajectories and motion patterns for both scenarios, without significant differences among them. High loads of individuals are observed in the vicinity of the staircases (represented in green colour). Moreover, the presence of clogging and arches-formation are observed in both scenarios. Black traces represent the traces being left for evacuated individuals. Meanwhile, individuals which have not yet evacuated the building due to artefacts and deadlocks (previously described on page 104) have left blue traces.

Evacuation times and their corresponding variations given in both scenarios are shown in Figures 6.16 and 6.19. The individual walking speeds registered for scenario (1) are shown in Figure 6.17. The characteristic decay observed in the walking speed (after around 370 seconds of evacuation) shows the presence of artefacts and deadlocks in the simulation (previously described in Section 5.3).

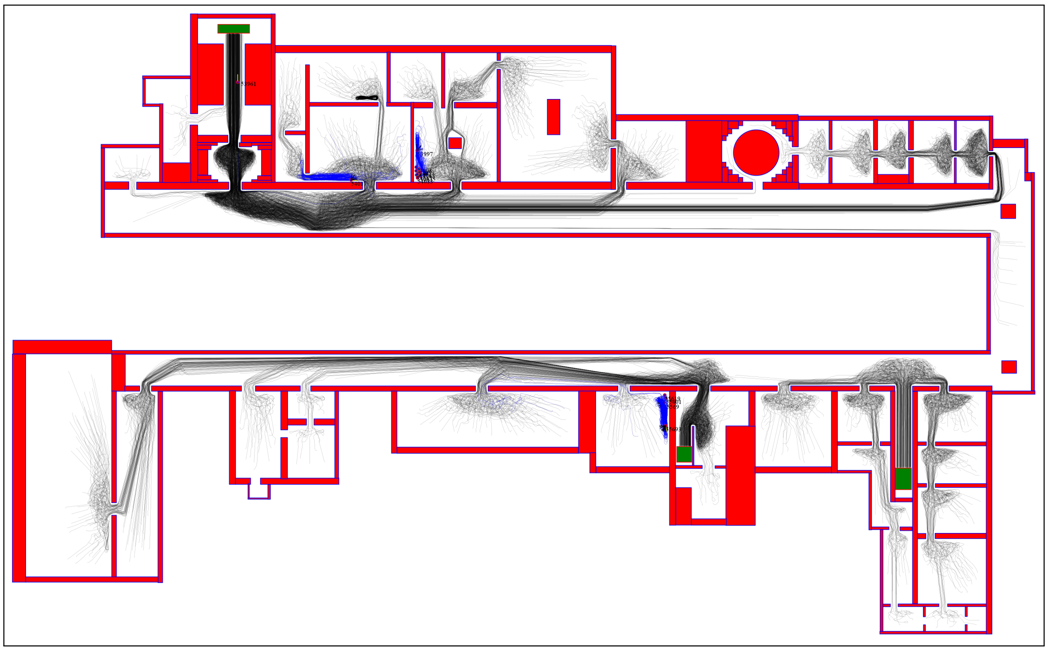

Figure 6.15: Resulting trajectories and motion patterns of test scenario (1).

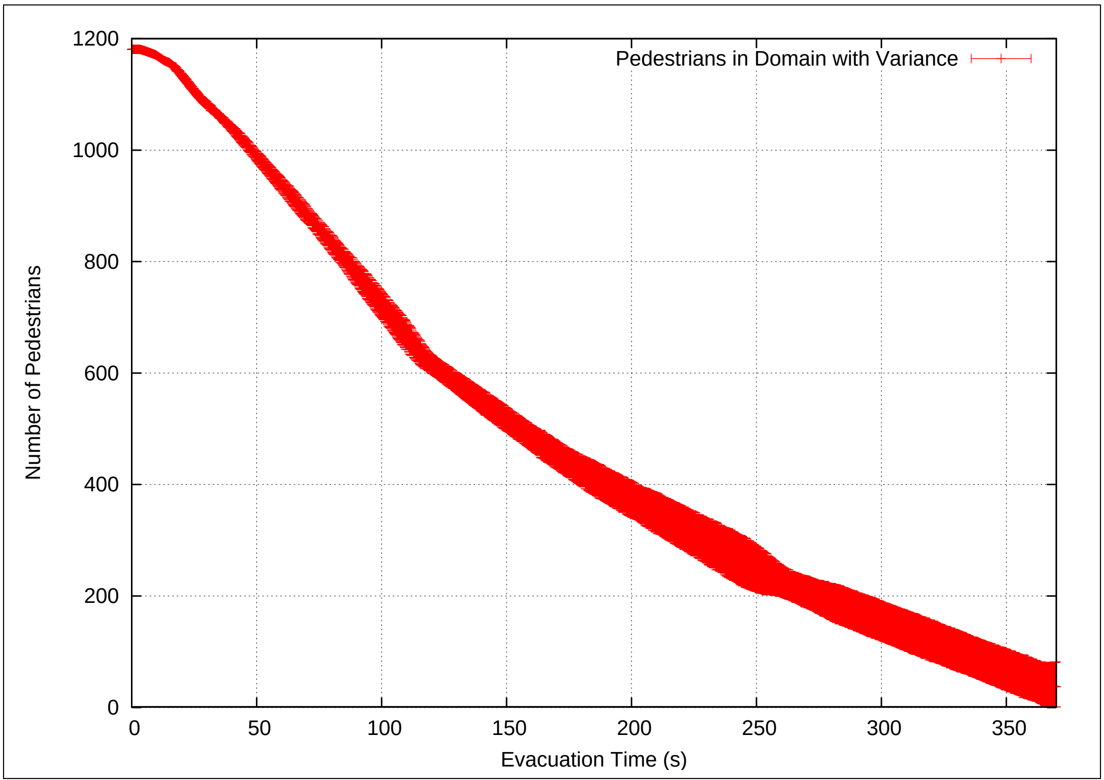

Figure 6.16: Mean values and the variance of evacuation times obtained for test scenario (1), after 70 random realisations.

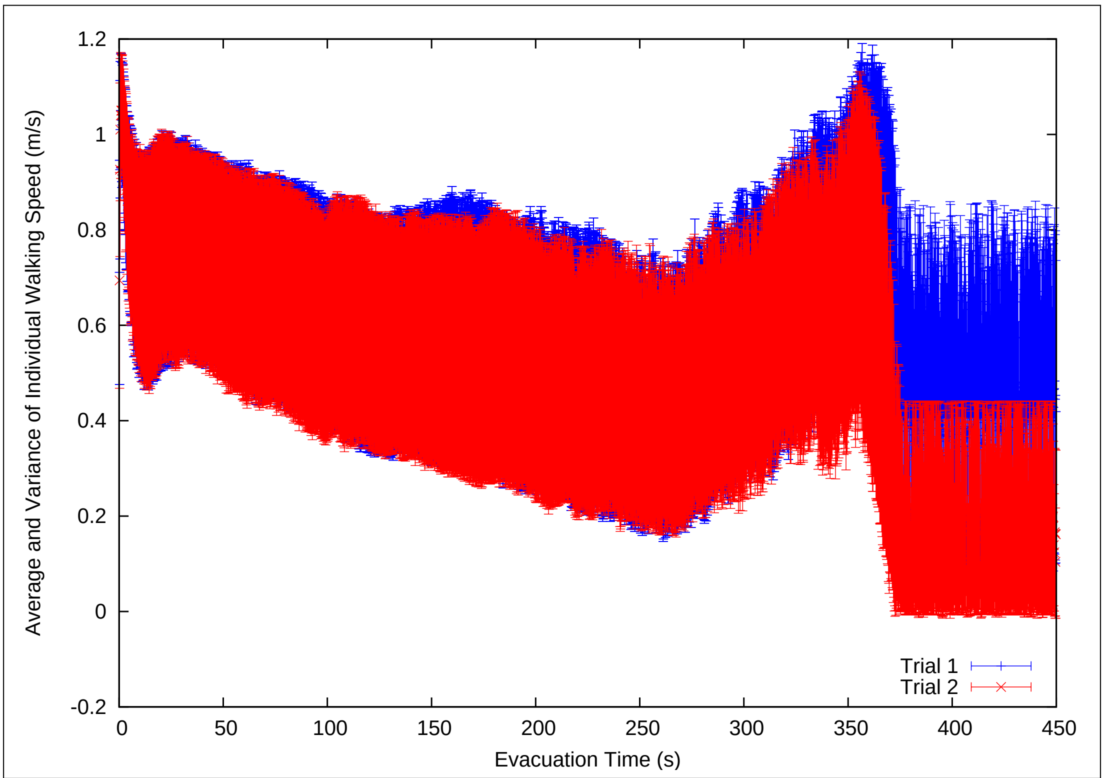

Figure 6.17: Mean values and the variance of individual walking speeds obtained of scenario (1), considering two trials.

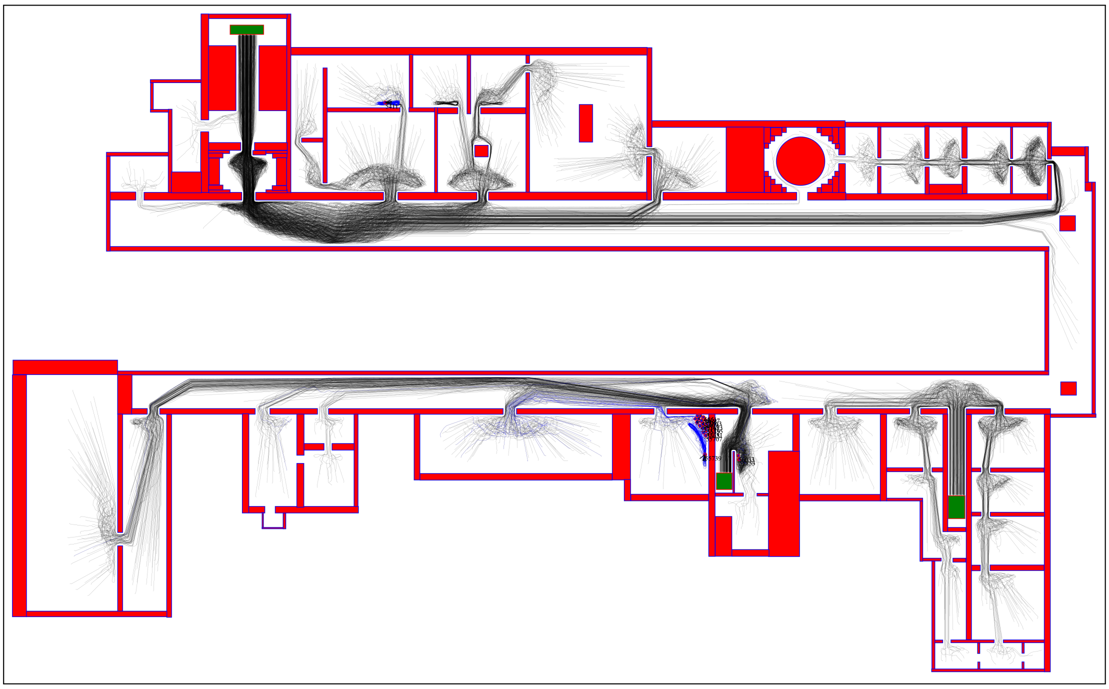

Figure 6.18: Resulting trajectories and motion patterns of test scenario (2).

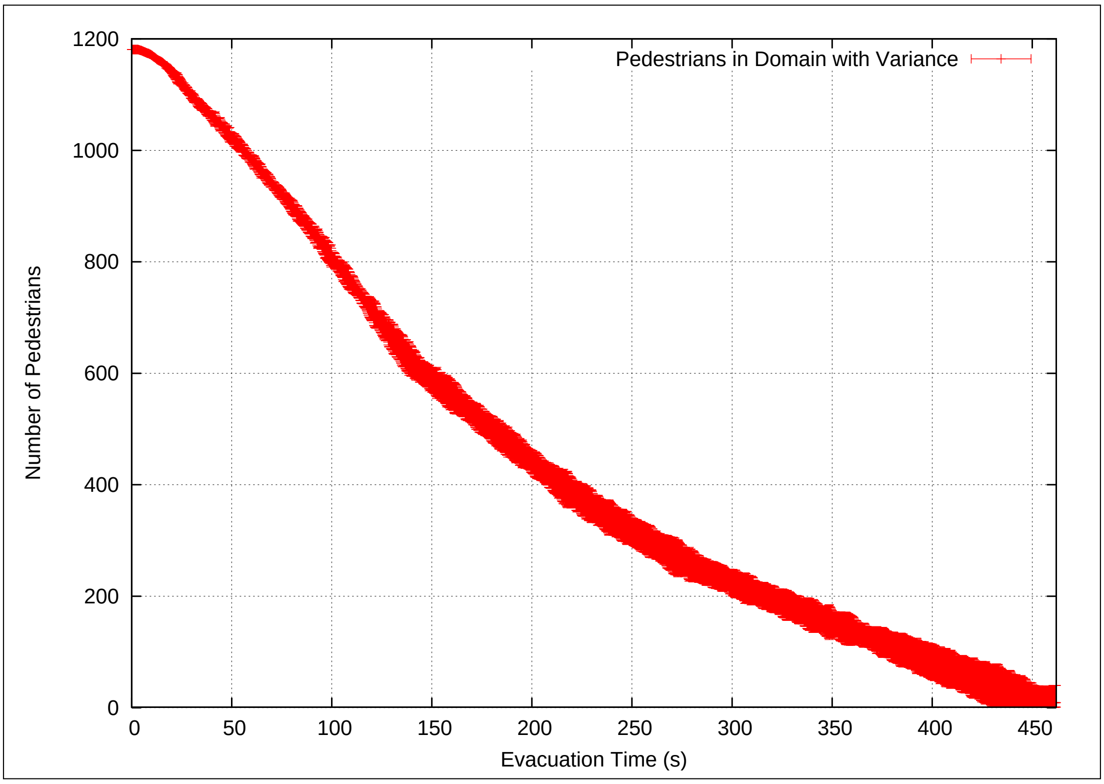

Figure 6.19: Mean values and the variance of evacuation times obtained for test scenario (2), after 19 random realisations.

6.4 Concluding Remarks on Numerical Results

In the context of risk management in the built environment, six case-study scenarios of the Uffizi Gallery were chosen, modelled and simulated. With regards to the demographic characteristics of the visitors to the gallery, three types of "averaged" individuals were introduced (Table 6.7).

Evacuation Traces

Regarding to the traces left (the trajectories and upcoming motion patterns) within the simulations, the following was observed:

- For all scenarios, no significant differences among the obtained trajectories and motion patterns were found.
- For the second-floor case, the presence of clogging and arches-formation was observed in scenarios (1) and (2). Specially in areas where a direct connection to the main corridor of the floor is not available. In the same way, high loads of individuals in areas near to staircases were observed. In particular, to the staircase which connect the main corridor of the second floor to the first floor and to the main access of the building (see Figures 6.15 and 6.18).
- In the case of the main exits, a significant increment in the load of visitors in the areas close to the staircases was observed. In particular, in the surrounding area of the main exit (entrance) of the building (see Figure 6.10).

Evacuation Times

With respect to the evacuation times, we can observe:

- Although there were no significant differences in trajectories and motion patterns of all scenarios, important increments of evacuation times were observed. In particular, for the scenarios with an equal mixture of visitors types (B and C).
- Moreover, an important increment of evacuation times in the ground floor is derived from the inflow of visitors of upper levels of the building to the main exits (see Figures 6.11 and 6.13). Although the number of individuals in the scenario was constant over the time due to the inflow of new

pedestrians from upper levels, tailback-like formations were not found. However, the introduction of the inflow of additional individuals of upper levels is recommended for future simulations of evacuations in intermediate levels of a building.

The mean evacuation times obtained from the simulations are given as follows.

Case-study	Scenario	Mean Evacuation Time (s)
Exhibition rooms 2-15	1	115
	2	136
Main-exits	1	55
	2	352
Second floor	1	374
	2	460

Table 6.8: Approximated mean evacuation times for different case-study scenarios.

However, the calculation of the total evacuation time of the Uffizi Gallery, shall include the simulation of the evacuation of the first floor and staircases. This remains as future work.

Walking Speeds

Regarding to the walking speeds obtained, the following was observed:

- At the start of an evacuation, we assume that all visitors are randomly allocated inside the building. Thus, in the first period of the evacuation we can instantly arise in the walking speed of the pedestrians. From this rapid movement, a decrease in the walking speed follows. In particular, because of the increasing influence of those new formed bottlenecks at the exits of the simulated scenarios. This was observed within the first 20 seconds of the simulations.

- After this time a relative low but constant walking speed is observed. When the number of individuals inside the building decreases, an increment in the walking speed of the individuals is observed. In all scenarios a characteristic "bathtub-like" curve for the walking speed was observed (see Figures 6.8, 6.12 and 6.14).

- The presence of artefacts and deadlocks (previously described in Section 5.3) can be easily identified as a strong and characteristic decay in the walking speed of the individuals produced in the last seconds of the simulated evacuation (see Figure 6.17).

Chapter 7
Summary, Contributions and Recommendation

The main body of the thesis ends in this chapter with a summary of key results, contributions to research and the recommendation to future works.

7.1 Summary of Key Results and Contributions

The findings and contributions to research of this thesis are summarised below:

- **The behavioural model (PerPedES).** The present study is focused on the development of a mathematical model based on visual perception for describing evacuation dynamics in normal situations (here assumed as controlled evacuations). Due to the lack of available differential equations with focus on perception in the literature, this work presents a first approach model. Thus, the model shall be understood as a proof-of-concept for the feasibility of such approach, where the introduced functions are not based on known laws from the literature. In general terms, the model describes the global dynamics of an evacuation by means of individual states. These states define the position $\boldsymbol{x}$ and walking direction θ of each individual within the evacuation. Changes in the individual states are influenced by the surrounding environment. An approximation to this influence is done by means of a modified ray-tracing concept introduced in the OO-visual perception model. Within the perception model, an individual psychology-like decision criteria based on the calculation of resistance and walkability is also introduced. Although the present study introduces a single type of decision criterion, the model approach is open for future extensions.

- **Model validation.** For the validation of the model, a tentative scheme is introduced. Within this context, simulations of evacuations in six test scenarios were achieved. The resulting traces of the simulated evacuations present similar characteristics to motion patterns described in literature. In particular, arch- and lane-formations, clogging-effect, movement in-coordination, overtaking- and collision-avoidance manoeuvres. Moreover, the numerical results present consistency to small time-steps. Meanwhile, convergence of the results is assured for time-step sizes below 0.2 seconds and for an amount of eight or more sampling rays.

- **Risk reduction.** Within the context of risk reduction in the built environment, this work is focused on the study of evacuation dynamics in historic buildings. Here the Uffizi Gallery was chosen as case-study. The behavioural model was introduced as a tool for the analisis of those factors affecting the vulnerability of the occupants when pursuing an evacuation of a building. In this sense, mean evacuation times and individual walking speeds registered for six scenarios were obtained together with the evacuation traces left by the agents.

7.2 Recommendation to Future Works

The research objectives outlined for this thesis end in this chapter. However, several questions still remain to be answered in future works:

- **Quantitative validation of the model.** The behavioural model has been validated by means of a tentative scheme. Within the realisation of the behavioural model the introduced functions together with their constants are not based on known laws from the literature. Thus, future works shall consider meaningful adaptions to our model together with a quantitative scheme of validation.

- **Optimisation of computation time.** Within the PerPedES model, the implementation of the ray-tracing scheme is the most important factor for optimising the performance. Due to the fact that a specially-formed ray was adopted, a utilisation of ready-made high-performance frameworks for ray-tracing was not possible. A common technique for speeding-up ray-tracing is to utilise a *quad-tree* for a fast geometric search. Another possible optimisation with regards to this problem would be the decomposition of the scenario into independently simulated parts, which would allow to parallel model execution for the subscenarios.

- **Elimination of deadlocks and artefacts.** The behavioural model is focused on modelling evacuation dynamics in normal situations (a so-called controlled evacuation). Thus, generation of forces in a sense of "pushing-behaviours" similar to those present in panic-like or emergency-scaled situations (which may loose possible blockages at the exits) are not considered in the model. Possible extensions of the agent geometry (e.g. by introducing an ellipse-based geometry) seems promising since it enables rotation-effects of the agents. By this means, possible deadlocks and blockages at the exits could be avoided. In addition to this, further specialisation of the walkability function shall introduce additional influencing factors. For instance, the introduction of psychological-stress-based functions as well as the introduction of a short-term-memory-like procedure for the recognition of past way-points.

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